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THE RESISTANCE OF 72 ELEMENTS, ALLOYS AND COMPOUNDS TO 100,000 KG/CM^2

By P. W. Bridgman

CONTENTS

Introduction 169

Apparatus and Method 169

Detailed Presentation of Data 184

Lithium 184
Sodium 185
Potassium 188
Rubidium 189
Caesium 190
Copper 192
Silver 192
Gold 194
Beryllium 194
Calcium 195
Strontium 197
Barium 199
Magnesium 200
Zinc 200
Cadmium 201
Mercury 202
Aluminum 205
Gallium 205
Indium 207
Thallium 207
Lanthanum 208
Cerium 213
Praseodymium 214
Neodymium 215
Titanium 216
Zirconium 216
Thorium 217
Carbon (Graphite) 218
Silicon 219
Germanium 221
Tin 221
Lead 222
Vanadium 222
Columbium 224
Tantalum 224
Arsenic 224
Antimony 226
Bismuth 228

Chromium 230
Molybdenum 231
Tungsten 232
Uranium 232
Selenium 232
Tellurium 233
Manganese 235
Iron 236
Nickel 237
Cobalt 238
Rhodium 239
Palladium 239
Iridium 240
Platinum 240
Intermetallic Compounds 241
Iron-Nickel Alloys 242
Silver Sulfide 244
Copper Sulfide 244
Molybdenite 245

Summary and Conclusion 245

THE RESISTANCE OF 72 ELEMENTS, ALLOYS AND COMPOUNDS TO 100,000 KG/CM^2

By P. W. Bridgman

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Introduction

In extending the range of measurement of electrical resistance at room temperature from 30,000 to 100,000 kg/cm^2 a radical change in technique is demanded. At room temperature there are no longer any liquids available with which to transmit pressure, for there is no substance ordinarily liquid which does not freeze at a pressure of 30,000 or less, and the permanent gases like nitrogen or argon freeze below 50,000 The only possibility is helium, which by extrapolation may be expected to freeze at 100,000, but the technical difficulties seemed so prohibitive in the view of experience with it to only 7,000 that its use was not even considered. This means that pressure must be transmitted with a solid, which means that the pressure will not be truly hydrostatic. It then becomes a problem to find a solid with as low a plastic yield point as possible and to find such a geometrical design for the apparatus that the effects of the unavoidable departures from a hydrostatic stress distribution are minimized.

Apparatus and Method

It was very soon evident that a solution could not be found by modifying the former apparatus with which extensive volume measurements have been made to 100,000.[1] This apparatus was completely supported on the outside surface by a liquid carrying hydrostatic pressure; that is, an inner pressure vessel nesting inside an outer vessel was used. It seemed hopeless to get electrically insulated leads into the inner vessel in the small space available, to say nothing of other difficulties.

Many preliminary attempts were made. The guiding idea of a number of these was to generate the pressure in a chamber of the proportions of a thin disc, so that the frictional effects at the edges would be a comparatively small part of the total stress load over the faces. The piston was made in the shape of a short boss on a massive block, in this way exploiting the support afforded by the surrounding unloaded parts. Carboloy was used in all this construction because of its superior strength. Much of the preliminary work was done with pressure chambers in the form of shallow depressions in the face of massive blocks. Such attempts to use a pressure chamber evacuated from the block were abandoned because of the fractures which invariably started from the corners of the depression, where

there are stress concentrations which are particularly harmful with a substance as brittle as carboloy.

During the preliminary work the possibility of using glass as a pressure transmitting solid was extensively investigated and for the first time measureably large plastic flow with permanent increase of density was observed in glass at room temperature. A disc of commercial lime glass 0.25 inch in diameter and 0.006 inch thick was compressed between two flat carboloy blocks to a mean stress of 100,000 kg/cm^2. Under this pressure there was a permanent decrease of thickness of 22 per cent, and a permanent increase of density from 2.497 to 2.617, that is, by 4.8 per cent. The glass, although copiously cracked, was not reduced to powder but was broken into clear blocks of the order of a millimeter or somewhat less on a side. Professor E. P. Larsen was so kind as to make an optical examination and found marked double refraction, with an increase of mean index for Na light from 1.515 to 1.527. Prolonging the time of loading does not perceptibly increase the permanent alteration, so that the behavior is *not* that of a viscous liquid. That is, under these conditions glass work hardens.

Another interesting effect was observed with glass. The carboloy blocks between which the glass was compressed were insulated from each other and connected to the same Kipf and Zonen high sensitivity short period galvanometer used in the final measurements. When pressure was increased to the fracture point of the glass, as indicated by the noise, the galvanometer was thrown into continuous spasmodic deflections to both sides of zero. The fracture of the glass would seem to be accompanied by electrostatic effects, perhaps due to intermolecular charges, and these give statistically a net charge fluctuating between positive and negative by a Brownian motion which is recorded by the galvanometer. It is not inconceivable that more detailed study of this effect would yield quantitative information on the intermolecular charges.

The method finally adopted is indicated in Figure 1. Two carboloy blocks, A and B, 1 inch in diameter and supported on the outside by shrunk-on steel rings C and D, are ground to have a flat central disc 0.5 inch in diameter with conical shoulders making an angle of 4° with the flat face. The 0.5 inch faces of the carboloy blocks are separated by a cell 0.010 inch thick, carrying the specimen whose resistance is to be measured embedded in the solid with which pressure is transmitted. Pressure is produced by pushing the blocks together in a hydraulic press; a very sturdily constructed press with piston diameter of 8 inches was used. Approximately 400 kg/cm^2 on the 8 inch piston suffices to produce 100,000 kg/cm^2 on the carboloy faces. The normal crushing strength of carboloy under simple compressive stress is in the neighborhood of 60,000 kg/cm^2. The

greater stress attained here is a consequence of the load being confined to only a portion of the block, so that the surrounding parts afford support for the highly stressed central disc. This principle of construction has been used in some of my other work.[2]

The solid medium transmitting pressure within the cell is AgCl. Measurements of the plastic flow strength under pressure [3] had already indicated that it is among the best solids available for this purpose. Preliminary experiments had also indicated that it is a sufficiently good insulator under

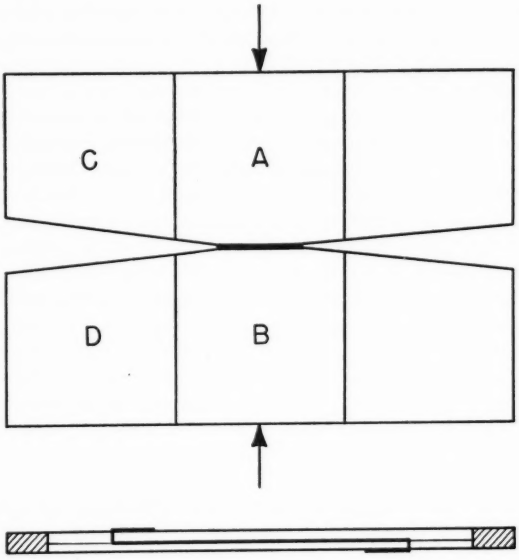

FIGURE 1. The apparatus for applying pressure to the resistance specimen. An enlarged section of the cell is shown in the lower part of the diagram.

the conditions for the use contemplated, that is, for the resistance of metals. The effect of pressure is to increase the resistance of AgCl. Dummy runs showed that no appreciable error was introduced under any of the conditions of this paper by conductivity of the AgCl. There would be serious difficulty, however, if an attempt were made to find the resistance of most semi-conductors by unmodified use of the same technique. AgCl is convenient for other reasons than its low plastic yield point and high electrical resistance. Its transparency is advantageous in properly position-

ing the resistance specimen within the cell, and it can be readily manipulated mechanically by squeezing out to thin discs of the required thickness, from which the discs are cut with a punch. The material used was single crystal stock which had been prepared by the Harshaw Chemical Company. I am indebted to Professor J. C. Street for making available for use in these experiments a rather large stock of this material which he had originally obtained for use in cosmic ray detectors.

The AgCl is prevented from leaking from the cell by an outer ring of pipestone (catlinite), a material which I have extensively used in insulating the leads in former measurements to 30,000. The pipestone seals the cell by friction. The outer diameter of the ring is 0.500 and the inner diameter 0.407 inch, making the width of the pipestone 0.047 inch. This, with a thickness of 0.010, ensures the maintenance of the seal by friction at any pressure provided only that the coefficient of friction is greater than 10/94 or 0.11. The effective coefficient of friction is materially higher than this and very little trouble was experienced from blowing out of the AgCl through the pipestone. Blow outs were further inhibited by subjecting the carboloy blocks to a preliminary application of pressure with less than the normal amount of AgCl in the cell. The result of the preliminary application is that a shallow annular impression is permanently left in the face of the carboloy; on future applications this helps to retain the pipestone from blow-out. The annular depression gradually deepens with continual use, until eventually the carboloy has to be refigured if it has not previously cracked. Contrary to my previous experience in measuring compressibilities to 100,000, I found that under these conditions carboloy work hardens to an appreciable extent, and the groove in carboloy blocks which have been refigured several times deepens much more slowly than in the virgin block.

The blocks may fracture in two characteristic ways: by radial cracks running down the conical shoulders but not in the flat faces, and by spalling off of flat slabs, sometimes in the flat face but more often from the periphery immediately at the boundary of the flat part. In many cases the radial cracks are not deep but are merely the cracks at the edges of thin flakes which spall off. The fracture of these blocks would make an interesting study for their own sake. In general, the fractures were as if the region immediately under the flat faces were being intruded bodily by the pressure into the massive block, in which it produces expansion and tensile cracks. This spalling off may well be due to expansion on release of load. Contrary to expectation, the harder grades of carboloy proved best for this purpose. Grade 905 was best with 883 next. The softer 779 and 55A were not so good.

Considerable work was done to find the best way of getting electrical

leads into the cell. At first the attempt was made to take the leads out through the pipestone sides, using thin flat strips of metal sandwiched between two pipestone rings. An advantage of such a procedure would have been that several leads could have been used, making possible resistance measurements by a potentiometer method, or the simultaneous measurement of several resistances, one of which could have been employed as a pressure gauge analogous to the manganin pressure gauge of former work. No successful method of doing this was found, the leads always being blown out by the internal pressure. The reason is doubtless the much lower plastic flow point of a crystalline metal as compared with the amorphous pipestone. Eventually the simplest possible method was adopted, the leads being taken out through the face of the AgCl discs, one making mechanical contact with one carboloy block and the other with the other. The resistance measured was the resistance between the two carboloy blocks, which was almost entirely constituted by the resistance of the specimen. For this measurement one of the carboloy blocks had to be insulated from the rest of the press; this was satisfactorily accomplished with mica 0.005 thick on the thrust surface of the block and a thin cylindrical shell of hard rubber on the cylindrical surface.

The resistance of the specimens in the cell was of the general order of 0.01 ohm. This was measured in the simple way suggested in Figure 2.

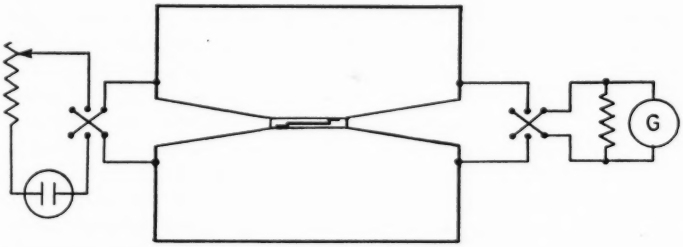

FIGURE 2. Scheme of the method of measuring resistance.

The blocks were tapped for current and galvanometer terminals. A suitable current from a dry cell was passed through the specimen from one block to the other and the difference of potential between the ends of the specimen (that is, between the blocks) determined from the deflection of a galvanometer in the potential circuit. For this a Kipf and Zonen short period galvanometer was used, of 56 ohms internal resistance, with 70 ohm shunt. Correction of the galvanometer deflections for failure of linearity with voltage was determined by special calibration. The controlling re-

sistance in the current circuit in general varied from 150 (the lowest in any of the set-ups) to several thousand ohms. For any one set-up this resistance was held constant. Constancy of the dry cell during the run was checked by direct determination of the galvanometer deflection with dry cell in series with a megohm before and after each run. Reversing switches in both galvanometer and current circuits permitted elimination of the effect of parasitics by taking the average of the four galvanometer deflections for the four switch combinations. Galvanometer readings were consistent and reproducible to 0.1 mm on a total deflection of approximately 10 cm, that is, to one part in a thousand. It will be seen that with the usual range of resistances the galvanometer deflections are proportional to the resistance between the blocks, that is, to the resistance of the specimen except for block and contact resistances. If the resistance of the specimen becomes too high, proportionality fails. The situation may then be met by more elaborate calculation, or if the resistance gets up into the order of ohms, as it sometimes did for special substances like tellurium and selenium, the circuits have to be rearranged. Any such rearrangement by combinations of series and shunt resistances is sufficiently obvious not to need detailed description.

With resistances as low as 0.01 ohm the most potent source of error proved to be contact resistance between the specimens and the blocks, and much time was spent in finding how to deal with it. It was fairly satisfactory to use intermediate electrodes between the specimen and the blocks of annealed gold 0.001 inch thick, but a completely satisfactory solution was finally found by using intermediate electrodes of annealed copper 0.001 inch thick, freshly amalgamated just before use and wiped to remove superfluous mercury. Blank runs with such electrodes gave values for the terminal resistances closely equal to the values roughly calculated by the conventional formulas (given by Jeans for example) for the resistance between a disc shaped electrode in the surface of a semi-infinite conductor and the body of the conductor. Geometrical irregularities made impossible an exact comparison of the measured contact resistance with the theoretical value, but in any event contact resistance was got down to a small fraction of the resistance of the balance of the specimen, and the method of correction was such that any influence of such resistance should correct out, as will appear in the future discussion.

The general method of mounting the resistance specimen in the cell and making contact with the electrodes is indicated in Figure 3. The cell is composed of two AgCl discs. The specimen, usually in the form of a single straight bar, is sandwiched between the two discs. Contact at the two ends is by means of amalgamated copper strips, threaded through radial slots cut in the disc in such a way as to be in contact with the

specimen on the inside and the carboloy block on the outside. The dimensions of the specimen varied with the material from 0.010 to 0.040 or even more inches wide, and from 0.001 to 0.004 inches thick. The length between the copper terminals was of the order of 0.18 inch. In order to avoid deformation of the specimen as far as possible when pressure is applied, the discs were preformed, after inserting the copper electrodes by stamping into them in a die a depression to take the specimen. Because of the difficulty of making depressions in the two opposing

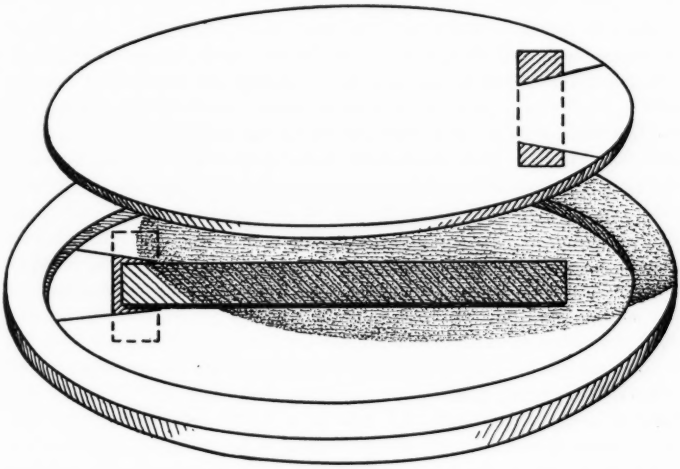

FIGURE 3. Details of the method of mounting the resistance in the cell.

discs of AgCl accurately enough to take the specimen without offsetting, the depression for the specimen was made in only one disc, which was made appropriately thicker to bring the center of the specimen to the center of the sandwich.

In order to avoid blow outs and at the same time permit as uniform a distribution of pressure as possible over both pipestone ring and AgCl the quantity of AgCl must be carefully controlled. In practise the pipestone ring was made first, by cutting off in the lathe a slice from a tube of pipestone machined to the correct inside and outside diameter. The thickness of a pipestone ring cut off in this way cannot easily be controlled to closer than 0.0003 inch. After cutting off its thickness is measured with an Ames gauge, and then the thickness of the AgCl disc adjusted

to somewhat better than 1 per cent by weighing and scraping to the value indicated by previous experience. The initial thickness of the AgCl prepared in this way was about 0.001 inch less than the pipestone, ensuring that pressure makes up first on the pipestone and seals the AgCl within. After assembling the resistance specimen in the AgCl sandwich, it is subjected to a final forming by pressing between flat pistons in a die, and then mounted in the pipestone ring, which it enters friction tight. It is then mounted between the carboloy blocks in a special subpress which is mounted as a whole in the 8 inch press. During mounting the disc is held concentric with a paper collar.

There is chemical action between many metals and AgCl, which may be decomposed with deposition of free silver. Such chemical action was completely suppressed in all cases by varnishing the surfaces of contact with a thin toluene solution of a resin which I owe to the courtesy of the Dupont Company. Not only did use of this resin eliminate chemical action but it also made marked, in some cases dramatic, improvement in freeing the stresses transmitted by the AgCl to the specimen of harmful shearing components. Without the use of the varnish certain metals were almost invariably torn completely apart after a pressure run, whereas with the varnish the only permanent effect was a small permanent increase of resistance with correspondingly small permanent change of dimensions. In consequence, the resin was used with all specimens, whether or not there was possible chemical decomposition.

The process of applying and releasing pressure is irreversible. The crushing strength of pipestone is comparatively small and its compressibility is nearly the same as that of AgCl, which, under 100,000 kg/cm^2, loses about 16 per cent in volume. These requirements rather severely limit the materials possible for the ring. When pressure is applied the pipestone crushes down, following the volume change of the AgCl within the cell, so that pressure is more or less uniformly distributed over the entire flat face. But on release of pressure the crushed pipestone cannot follow back beyond its elastic range, which however appears surprisingly large under these conditions, so that eventually the pipestone ring begins expanding radially, pushed by the expanding AgCl within. This terminates sometimes in a blow out, although usually not, but in all cases terminates in an irreversible permanent radial stretching of the AgCl disc and the embedded specimen. The result is that acceptable resistance measurements can be made only on the increasing branch of the cycle, and this means incidentally that readings can be made only on the initial application of pressure. A preliminary pressure seasoning, such as was previously regularly employed up to 30,000, is therefore impossible. However, this should be of little consequence with pressures as high as these, which are

presumably much beyond any initial internal stresses in the material. Readings were as a matter of fact always made with decreasing pressure as well as with increasing, but such readings could be used only by way of check or confirmation of questionable points.

An important preliminary question was to what extent the pipestone ring supports the load and prevents transmission of the average pressure to the AgCl within. Information about this afforded by the resistance measurements themselves was ambiguous because of uncertainty in the correction to be applied for non-hydrostatic components in the stress, as will appear presently in the discussion. Fortunately an independent method of answering this is afforded by the polymorphic transitions which are exhibited by a number of the materials measured here. At such a transition there may occur discontinuities in resistance, and by locating the discontinuity the ostensible pressure of the transition may be determined. To be suitable for this purpose it is necessary that the transition run sharply with little or no over-shooting, and that the accompanying discontinuity of resistance be large. Fortunately there are at least two such transitions, the I–II transition of bismuth at approximately 25,000 kg/cm^2, and the I–II transition of thallium at approximately 45,000. Checks on the pressure within a few per cent were obtained at both these points. The agreement was within the uncertainty due to the other corrections about to be discussed, and in all calculations the pressure was taken at its ostensible value, directly calculated from the areas and the pressure on the low pressure end of the 8 inch press. This latter was controlled with a dead weight gauge.

The procedure consisted in successively adding increments of weight to the load on the dead weight gauge and making the four galvanometer readings. The dimensions are such that no time was required for dissipation of thermal effects after each change of load, and a run could be rapidly made, always in less than an hour. For the first study of a new material, readings were made with 23 equi-spaced pressure points with increasing pressure and about half as many with decreasing. If the first run disclosed no incidents requiring closer examination subsequent runs might use only 11 points with increasing pressure and 5 with decreasing. In this case the points were more closely spaced at the lower end. There were perceptible initial effects due to the crushing of the pipestone; for this reason the first reading was always made at 5,500 kg/cm^2. Under this pressure the pipestone was sufficiently crushed and the electrodes were pressed into sufficiently close contact with the carboloy so that there were no further low pressure irregularities.

As an indication of the smoothness and regularity of the readings there is shown in Figure 4 the directly determined readings for tungsten, resist-

ance in terms of galvanometer deflection in centimeters, against pressure in terms of the weight on the pan of the dead weight gauge. Tungsten is one of the metals for which greater irregularities than average might be anticipated, because of its high elastic limit, permitting the accumulation of high non-hydrostatic pressure components of resistance change. In the following detailed presentation of data the range of resistance change for the four runs is given, permitting further estimation of the probable accuracy.

The most serious problem connected with the use of the new technique is to devise a method for correcting for the non-hydrostatic components

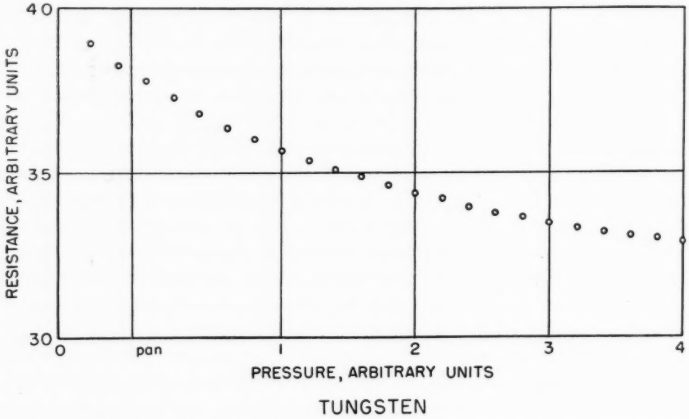

FIGURE 4. Uncorrected readings of the resistance of tungsten. Ordinates are resistance in arbitrary units (galvanometer deflection) and abscissae pressure in arbitrary units (weights on the dead weight piston gauge).

of stress. We may set as the final object of the measurements to determine the effect of hydrostatic pressure on the resistance of a specimen with electrodes rigidly attached to its surface, the electrodes experiencing the same deformation under pressure as the body of the specimen. It was this that was measured previously up to 30,000 kg/cm^2 on specimens exposed to truly hydrostatic pressure. This may be called the "direct" resistance, and the corresponding pressure coefficient the "direct pressure coefficient." If it is desired to find the effect of pressure on specific resistance, the direct coefficient may be converted to coefficient of specific resistance with the help of the cubic compressibility, which is known by previous measurement for most of the substances of this paper. This

conversion can be made uniquivocally only for substances electrically isotropic, that is, for substances crystallizing in the cubic system.

The conditions in the present experiments differ from previous conditions in the failure of the stress to be hydrostatic. This failure results in two sorts of effect; specific effects of shearing components of stress on resistance and gross overall effects due to change in the geometrical shape of the specimen under the distorting effect of applied shearing stress. These two effects may each be considered within the elastic and the plastic range.

Comparatively little is known about the effect of shearing stress on resistance. There are measurements on the effect of simple tension in the elastic range on a number of metals [4] and it is known that there is no rule about even the sign of the effect, for examples are known of both increase and decrease of resistance under tension. There seems to be no connection between the sign of the tension effect and the sign of the normal hydrostatic pressure effect. The presumption is therefore that under the conditions of these experiments components of shearing stress may either increase or decrease resistance. Less is known about the behavior of resistance during plastic flow. There are a number of experiments on the permanent change of resistance produced after permanent stretching and release of stress, but apparently nothing has been done to find the effects during plastic deformation while the deforming stress is still acting, which are the conditions here. The natural presumption is that in the plastic range changes in specific resistance are of minor importance, but preliminary experiments which I have undertaken indicate that the situation is not simple. Another factor to be considered is to what extent the elastic range of distortion is extended by mean hydrostatic pressure in these experiments. Experiments on steel have indicated an increase in the elastic limit under tension of between 15 to 30 per cent under a pressure of 30,000 kg/cm^2. It is not unreasonable to expect under present conditions extensions of the elastic range of 100 per cent or more under top pressure. The result of all these considerations is that it is impossible to make any general statement about the intrinsic effect of shearing stresses in these experiments, but that effects of either sign may be anticipated. The magnitude of such effects is probably a not large fraction of the true hydrostatic effects because 100,000 kg/cm^2 is so far in excess of the normal shearing flow stress for the materials measured here.

The gross over-all distortion of the specimens due to being embedded in the AgCl is complicated and compounded from effects arising from distortion of the carboloy parts and volume compression of the AgCl. Consider first the ideal case in which the carboloy is infinitely rigid so

that the plane faces of the cell remain plane under pressure and with unaltered diameter, and the only distortion is a thinning of the cell because of the volume compression of the AgCl. To a first approximation, assuming a low plastic yield stress for the AgCl, the distortion of the AgCl consists of a shrinkage perpendicular to the face of the disc of an amount three times the normal linear shrinkage under the mean hydrostatic pressure, but no change in the direction of the two dimensions of the face. This distortion is that produced by a mean hydrostatic stress on which is superposed a mean two dimensional distending stress in the plane of the faces expanding the surface dimensions back to initial. This two dimensional distending stress is afforded by friction in the faces and may be assumed comparatively small in view of the low plastic flow stress. Embedded in the AgCl deformed in this way is the specimen. To a first approximation the stress acting on it is hydrostatic, and the first effect is to produce in the specimen its normal hydrostatic compression, under which the specimen shrinks uniformly in all directions. But the specimen is more or less effectively embedded in the AgCl and is therefore dragged out in the dimensions of the face and correspondingly thinned. The net effect is that the specimen is longer and of smaller cross section than it would be if subjected to pure hydrostatic pressure. Both of these distortions increase the resistance. Hence if the specimen is one of the normal metals for which the effect of pressure is to decrease resistance the change of resistance under pressure as determined in this experiment will be too small in so far as it is affected by this effect. Conversely, if the pure hydrostatic effect is to increase resistance, too large an increase of resistance will be found in these experiments. The corrections for this effect may readily be worked out in terms of the assumed known compressibility. It will be found as a matter of fact that the effect is in accordance with expectations with regard to sign for a number of the softer metals, which are also the more compressible metals, provided those metals have a normal negative pressure coefficient of resistance. But this correction gives the correct sign for the abnormal metals with positive pressure coefficient only in one doubtful instance, and then with very poor numerical agreement. The conclusion would seem to be that the effect due to dragging of the specimen by differential compressibility is of minor importance.

A much more potent source of deformation than differential compressibility arises from the deformation of the carboloy blocks. The solution, credited to Hertz, is well known for the deformation of a semi-infinite block loaded over a circular disc on its face by a uniformly distributed pressure. Under such a distributed pressure the circular disc is depressed at the center, or in other words, the cell between the two carboloy blocks

assumes the shape of a double convex lens. Calculation shows that the curvature of this lens becomes very appreciable at the top pressure. The lenticular distortion of the carboloy may be demonstrated experimentally by replacing the cell of pipestone and AgCl with a solid disc of lead. The plastic strength of lead is so low that it may be assumed that it exerts a uniformly distributed pressure on the carboloy block. On applying pressure to such a lead disc, lead is extruded until the edge thins down to practically nothing and the lead trapped in the interior takes the form of a double convex lens of thickness at the center of 0.0028 inch, or nearly 30 per cent of the initial thickness of the cell. This thickening at the center is accompanied by a flow of AgCl toward the center, which carries the specimen with it to a certain degree, thickening and shortening it. This deformation decreases the resistance, which is thus a change in the opposite direction from that arising from the differential compressibility. It is a fact that most of the metals, particularly those with small pressure coefficients, show in these experiments larger decreases of resistance than would be expected from former measurements. The lens effect may be presumed to be the major effect in most cases. It cannot be calculated, since the conditions from one experiment to another vary too much. Slow progressive deformation of the carboloy due to sinking of the pipestone groove may be mentioned as one such factor.

Another cause of imperfect reproducibility is the crystalline structure of the AgCl. The original material was usually one crystal and even after it had been pressed into discs of the proper thickness it retained a large degree of unicrystallinity, as shown by the slip lines often evident on the surface after an experiment. Internal slip in the AgCl would tend to deform the specimen, and in a way depending on the particular orientation; this is not a reproducible factor.

The indirect evidence is that the deforming effect of the AgCl is much less than it would be expected to be if the specimen were rigidly embedded in the AgCl and dragged with it without slip. Rather, most metals slip through the AgCl with comparatively little drag, and the stresses are much more nearly hydrostatic than I feared at first or indeed was indicated by the preliminary experiments. The use of the resin varnish has a very large ameliorating effect in suppressing drag. There is one rather specific piece of evidence with regard to the small amount of drag. It is known that AgCl has a polymorphic transition at 90,000 kg/cm^2, with 1.6 per cent decrease of volume.[5] If the drag between the specimen and AgCl is large it would be expected that all specimens would show some incident in the pressure-resistance relation in the neighborhood of 90,000. Actually the smoothness of the resistance curve was disturbed in only a very few cases, and these were for the softest metals, such as sodium,

where it would be expected. It would appear that most metals become stiffer than AgCl under pressure and slip through it with little drag.

In spite of serious attempts, no satisfactory way was found of combining these various effects into a single theoretically determined correction for converting the changes of resistance as measured to the effect of a pure hydrostatic pressure. The only course was to put the correction on an empirical basis, determined in such a way as appeared most intrinsically reasonable in the light of all the data, and also determined so as to correct the values to the known values previously found in the range up to 30,000 kg/cm^2 for pure hydrostatic pressure. Fortunately this latter information is available for nearly all the substances of this paper.[6] The "intrinsically reasonable" may appear to be a poor guide in penetrating into new territory, where a large part of the element of adventure consists in finding effects that were not anticipated, that is, that were not "intrinsically reasonable." However, there can be no question that physics does have to proceed in some such way in getting into new territory, and in the following discussion of the most plausible way of determining the corrections considerations will appear *in parvo* typical of what has been done by others on a grander scale many times in the past.

In the first place, in view of the many problematic factors introduced by stress propagation by a solid, more measurements were made on each substance than usual. Four sets of measurements have been made on most of the materials of the following. This involved altogether more than 300 set-ups and runs. The dimensions of the four specimens were usually varied so as to produce variation in the presumptive corrections; usually two different widths were used. For each substance two different sets of carboloy blocks were used, of different grades of carboloy and with geometrical variations which might rise to as much as 15 per cent on the thickness arising from variations in the pipestone rung. No consistent differences were found that could be associated with the grade of carboloy (this involves the elastic constants of the carboloy) or with geometrical differences. In fact, no consistent factor of variation of any sort was found. Certain substances were much more suggestive in giving presumptive information about the best correction than others. For instance, if the absolute value of the pressure effect is small, and if the correction is capricious, it would be expected that one run might give a positive sign for the pressure effect and another a negative sign. Such behavior was almost never found; the substances with small effects showed consistently the same sign on all set-ups. The same sort of thing was shown by substances with flat maxima or minima. These always occurred at approximately the same pressure with different set-ups. Or

if the curve of resistance against pressure reverses curvature, it was found that the pressure of reversal was the same for different set-ups, and therefore presumably of real significance. It was therefore assumed that all such effects were real and were not to be removed by the correction, as could easily happen. For instance, a correction linear in pressure is capable of removing a flat minimum.

The problem was therefore, how to find a correction which would produce agreement with the former results up to 30,000 and not remove the special features disclosed at higher pressures, of which there were an unexpectedly large number. In general it was not safe to extrapolate the present readings to zero pressure, the lowest readings being at 5,000 with usually obvious irregularities at the lowest pressures. The best range for comparing the present with former values was between 20,000 and 30,000, not infrequently running the present values down to 10,000. In many cases, particularly for those substances with absolutely small effects, it seemed safe to run the former results by extrapolation to 40,000 or even in a few cases to 50,000 for comparison with present results. The simplest process of comparison was to take the ratio of present to former resistance increments, from 30,000 as the fiducial pressure, and to plot these ratios as a function of pressure. If the ratios were approximately constant, well and good, and the present measurements in the new range were corrected by this constant. If the ratios were not constant, as was usually the case, they might show comparatively little variation and might vary in such a way that a curve could be plausibly extrapolated.

In general, selection of the most plausible correction was made from a few simple types of correction. Of these the simplest are additive and multiplicative corrections. It is to be distinguished whether the addition or multiplication is to be performed on the total resistance or on the change of resistance from some fiducial point. Each type of correction has its specific effect in altering such characteristic features of the original measurements as maxima or minima or points of inflection, and choice of the type of correction was made with this in mind. The type of correction also depends on the estimate made of the probably dominant factor in the correction. For instance, if the dominating factor in the correction is the effect of shearing stresses and if it may be assumed that these remain in the elastic range, then the correction will be a multiplicative correction on the measured change of resistance which will be proportional to the pressure. On the other hand, if the dominant effect is due to change of geometrical shape due to drag and plastic deformation, then the effect is independent of the specific effect of pressure on resistance for the particular substance and is an additive correction on the total resistance, this additive correction being a definite fraction of the

total resistance at any given pressure and itself being a function of pressure to be determined if possible from the low pressure comparison. If the shearing stress effect is one which is elastic in the low pressure range but becomes plastic at the upper end of the range, then the presumption is that there is little change in the correction at the upper end and the correction curve may be extrapolated graphically to an asymptote at the upper end. Such an asymptotic extrapolation was employed in a number of cases. It would not be feasible to reproduce all the arguments by which the method of correction was determined in every individual case; any notable features will be mentioned in the following under the detailed description of the different materials. The whole process was a tentative one of feeling one's way, but feeling one's way in a manner suggested by the whole body of experience with all the experimental material (the final results were not calculated until all the experimental material for all substances was in), which would be difficult to communicate or justify to another, and which will have to be accepted as my opinion as to the most probable values. Fortunately the corrections are not large enough to obscure the essential qualitative nature of the results, and in a number of cases closely concordant results were obtained by applying different methods of correction.

The detailed presentation of data now follows. Elements are given first, arranged in chemically similar families (columns of the periodic table) beginning with low atomic weights, that is, with the alkali metals. Elements are followed by "intermetallic compounds," and these by an unsystematic collection of a number of iron-nickel alloys, and finally three semi-conducting compounds.

Detailed Presentation of Data

Lithium. Because of their chemical activity in air all the alkali metals require special methods of handling during mounting in the cell. Lithium is the least active of these and was easiest to handle; the same general method was used for all. The specimen was squeezed to the right thickness and cut to final dimensions under a heavy oil. It was then washed under petroleum ether or pentane. The dummy cell had meanwhile been prepared with pipestone and AgCl discs of proper dimensions. The cell was then mounted in a glass cylinder with rubber stoppers at the two ends through which passed two pistons and a vacuum connection. The cell, in place on the flat face of one piston, was filled with pentane and the specimen placed in the cell without losing protection by pentane during the process of transfer. The upper stopper of the glass cylinder was inserted, and the pentane evaporated with a vacuum pump. After evaporation the cell was closed by pushing in the upper piston through

the stopper and consolidated in an arbor pressure before removing from the cylinder. The seal between the two AgCl discs thus produced was always adequate, even for so reactive a substance as caesium. The resin varnish played an essential role in securing this seal.

The lithium was from my former stock, with which all my previous measurements have been made. The purity has been proved to be adequate. Eight different set-ups and runs were made. The first four runs were made before all the details of the technique of preforming the AgCl to the shape of the specimen had been worked out. This preforming proved to be specially necessary for the softer metals like lithium, as shown by certain irregularities in the first runs not found in the later ones. The first four runs were discarded in the final result. All four final runs agreed in showing certain unusual qualitative features with regard to curvature. The resistance of lithium is known to increase initially under pressure with upward curvature. All four present runs showed this initial upward curvature, but less markedly than the former measurements. This curvature reversed in the neighborhood of 20,000 to concave downward, followed again by a point of inflection and reversal to upward curvature in the neighborhood of 60,000, from which up to 100,000 the upward curvature becomes continually more pronounced.

The directly measured proportional changes of resistance between 30,000 and 100,000, taken from 30,000 as fiducial, ranged from 0.232 to 0.301, mean 0.261. This proportional change of resistance was about 33 per cent less below 30,000 than given by former measurements.[7] It suggests itself that the difference is chiefly due to flow of AgCl toward the center because of lenticular thickening of the cell; such an effect would be expected to be large for the softer metals. The best way of correcting to secure agreement with former values is more difficult to decide here than often because the reverse curvature now found shows that it is not safe to extrapolate the former results beyond the range of measurement. The course adopted, which has the advantage of preserving the characteristic reversals of curvature, was to apply an additive correction proportional to pressure. This is nearly equivalent to applying a multiplicative correction of 1.5 to ΔR, but this latter would have obscured the reversals of curvature. The result of applying the correction was to change an uncorrected proportional resistance of 1.169 to 1.239 at 30,000, and from 1.475 to 1.704 at 100,000. The final results are shown in Table I and in Figure 5.

Three of the four final runs showed a disturbance above 90,000 doubtless associated with the transition of AgCl. The numerical value of the disturbance varied considerably, but in sign it was a decrease of resistance.

Sodium. The material was stock used in former measurements. Mechanical softness gave no particular difficulty in handling during setting up the

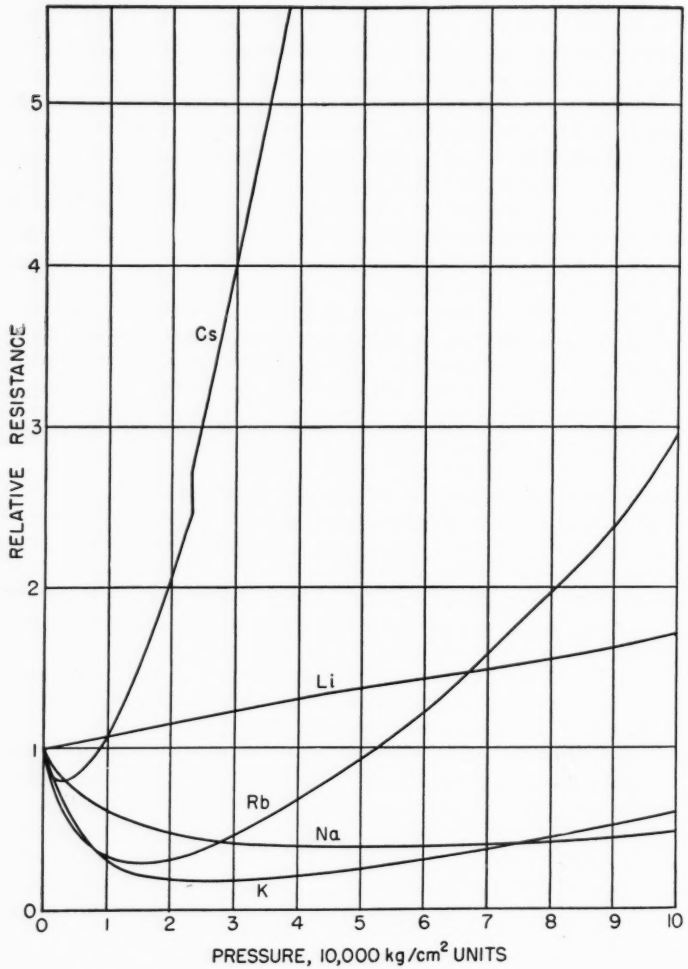

FIGURE 5. The relative resistances of the five alkali metals as a function of pressure.

TABLE I

Pressure kg/cm²	R/R₀				
	Lithium	Sodium	Potassium	Rubidium	Caesium
0	1.000	1.000	1.000	1.000	1.00
10,000	1.073	.618	.303	.326	1.09a
20,000	1.152	.483	.182	.309	2.12
30,000	1.239	.413	.178	.455	4.20b
40,000	1.305	.392	.203	.695	5.96
50,000	1.366	.390	.252	.924	8.90
60,000	1.428	.399	.309	1.218	9.32c
70,000	1.487	.412	.370	1.594	7.55
80,000	1.551	.430	.439	1.972	6.55
90,000	1.623	.452	.514	2.38	5.88
100,000	1.704	.479	.596	2.95	5.33

[a] Minimum of 0.80 at 2.500
[b] Transition at 22,000; resistances 2.44 and 2.70
[c] Maximum of 11.2 at 54,950 kg/cm²

cell. Four runs were made, all in close agreement. There is a minimum in the resistance in the general neighborhood of 45,000, here observed for the first time. Such a minimum was anticipated because of the known minima at less than 30,000 of potassium, rubidium, and caesium.

The measured changes of resistance below 30,000 are of the general order of 15 per cent less than given by former measurements to 30,000.[8] This is in the direction to be expected from the effect of differential compressibility. Because the compressibility of sodium is high, it would be expected that these runs would be capable of giving particular information about the validity of the correction for differential compressibility. Accordingly a rather elaborate formulation and application of this correction was made. The correction is proportional to $v^{2/3}$. The result of applying the correction yielded such improbable results that it was rejected. The correction resulted in displacing the minimum to 80,000 and in flattening it almost to the vanishing point. The internal evidence is that the minimum is to be taken nearly at its face value, because the minima found for potassium and rubidium are at the same pressures as found previously. Accordingly a mathematically simple scheme of correction was adopted which preserves the features felt to be qualitatively correct. This was approximately equivalent to multiplying the proportional changes of resistance, taken from 20,000 as fiducial, by a constant factor. The uncorrected and the final results are shown in Figure 6. The correction is such that the corrected and the uncorrected curves will cross at a little above 100,000, where the resistance has again the value at the arbitrary selected fiducial point, here at slightly less than 20,000 kg/cm². This fiducial point can have

no absolute significance, but except for this the method of correction was the most plausible that I could devise.

The final resistances in terms of the resistance at atmospheric pressure as unity are given in Table I. The minimum is in the neighborhood of 46,000. Previous measurements to 30,000 had suggested by extrapolation a minimum in the neighborhood of 40,000.

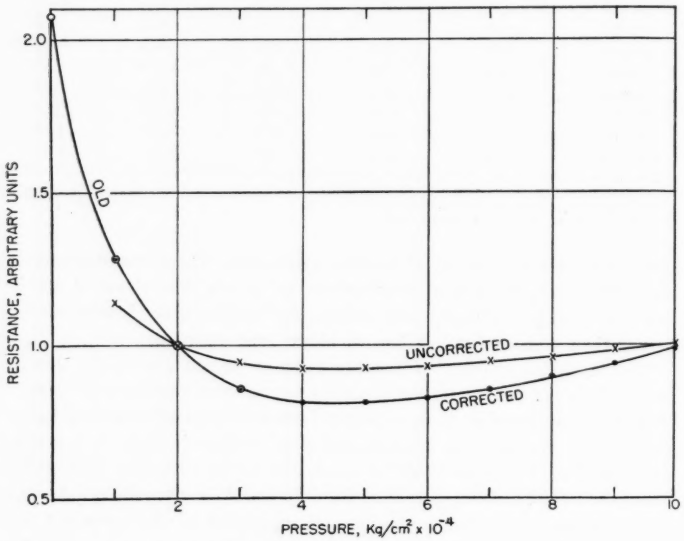

FIGURE 6. The resistance of sodium, showing in one diagram the former values to 30,000 kg/cm², and the present uncorrected and corrected values to 100,000 kg/cm².

Potassium. The material was from former stock, kept sealed under nujol. Manipulation was beginning to get troublesome because of mechanical softness and chemical activity. Four runs were made with qualitatively good agreement. All runs showed a sharp minimum in resistance at a pressure not differing by more than 1,000 kg/cm² in either direction from 25,000 kg/cm², against a previously observed value of 25,400. On the other hand, the magnitude of the relative changes of resistance below 30,000 were much less than formerly.[9] Divergence in this direction would be expected because of differential compressibility, which is markedly larger for potassium than for sodium. The best method of correcting the

present values to agree with the former is particularly problematical here because of the minimum in the middle of that range, 20,000 to 30,000, which for most materials affords the most secure basis for the comparison and the reduction. Correction was finally made by multiplying the observed changes of proportional resistance taken from 20,000 as fiducial by the constant factor 2.56, this being the factor required to correct the present values to agree with the former ones at 10,000. The final values so corrected are shown in Table I and Figure 5. It must be recognized that there is unusually large uncertainty in the upper end of the range. There can be no question I think, however, of the qualitative features of unusually marked upward curvature and the fact that at 100,000 resistance is still considerably short of rising back to the initial value at atmospheric pressure.

Potassium showed more markedly than lithium or sodium a disturbance in resistance between 90,000 and 100,000 presumably due to the transition of AgCl. In all cases the resistance dropped somewhat. The values given in the table were obtained by smooth extrapolation from 90,000 to 100,000.

Rubidium. This was old stock, kept sealed under nujol. It had been previously purified by slow distillation. This metal was so soft mechanically that a modification of the technique applicable to the first three alkalies proved necessary. The dimensions of the specimen had to be accurately controlled to fit the depression preformed in the AgCl. Too little material may result in pinching through the specimen when applying initial pressure to the cell, because with this excessively soft material the situation is entirely dominated by flow in the AgCl. Too much material results in its extrusion between the two AgCl discs, sometimes with short circuiting between the carboloy blocks. The method adopted was to extrude the rubidium to wire of a diameter selected so that when cut to length and squeezed flat it just filled the preformed pocket. The diameter of the wire meeting these requirements was 0.013 inch, squeezed flat to about 0.004 inch thick.

Four runs were made with good qualitative agreement. All runs showed a minimum resistance near 20,000 kg/cm^2, against 17,000 found before. The best method of securing agreement with previous results [10] was made even more difficult to determine than for potassium by the presence of the minimum in the range of most effective comparison. There was the further complication that the former results were not for the free specimen, but were for the specimen as encased in a glass capillary. These former results for the constrained specimen were first corrected to the free specimen by assuming an average value for the compressibility of the glass envelope. The correction changes the former value for the proportional resistance at 30,000 from 0.576 to 0.454. The correction finally adopted involved a correction of about 40 per cent on the total resistance and a

correction on the *change* of resistance by a factor of 2. It would probably be difficult to justify this in detail, but the method does have the virtue of giving agreement with the former values to 30,000, and preserving the two not very pronounced points of inflection shown consistently by all four runs. These points of inflection are similar qualitatively to the points of inflection shown by lithium, and although not so pronounced are presumably real. The final values are given in Table I and Figure 5. It will be noticed that the final resistance at 100,000 has risen to be markedly larger than the initial resistance at atmospheric pressure, unlike potassium and sodium. The difference between the three metals in this regard changes progressively as is to be expected.

Caesium. The material was former stock, stored sealed in glass in *vacuum*, not in oil. It had been purified by slow distillation to have a sharp freezing point and to show a silvery color in contrast to the usual golden color due to dissolved oxide. The mechanical difficulties in manipulating this substance proved to be really formidable, and I was glad to have three usable runs after many attempts. Not only is the mechanical softness extreme, but the melting point is so close to room temperature that it was necessary to work with precooled tools and in a cooled room. Worst of all, the chemical activity is so great that it attacks liquids effective with the other alkalies in preventing action by air during assembly. Action by pentane was rapid and even with pure i-octane the action was too rapid. It was apparently not known to the organic chemists that caesium attacks these purified hydrocarbons. It was finally found that the action with nujol was slow enough to offer prospects of success, but this demanded a change in technique of assembly which was not easy. The caesium, extruded into wire, was transferred to position in the cell while still wet with nujol, and formed in its preformed seat with a spatula by hand. The nujol had to be then removed with blotting paper, precisely controlling the removal so as to leave a film of nujol thick enough to prevent chemical action by air during the few minutes of the remaining manipulations, and not so thick as to prevent the two AgCl discs from sticking together on consolidating the cell in the arbor press. Once sealed, the resin varnish was completely effective in preventing further chemical action, but on release of pressure after the run, the caesium broke out of the cell by differential expansion, acting essentially like a liquid, and was speedily destroyed by chemical action with the air.

The most important question to be answered by the measurements was the nature of the resistance change on going through the recently discovered electronic transition at 45,000, a transition in which the crystal lattice is unaltered, but in which there is a large change of volume.[11] Three usable runs were made; two of these gave acceptable values only above 30,000,

there being some unexplained disturbance at low pressures presumably connected with geometrical changes in the configuration forced by the AgCl. At higher pressures the internal evidence is that the caesium becomes stiff enough to dominate, and readings of all three runs showed a gratifying smoothness above 30,000. Only one of the three runs showed a slight disturbance above 90,000, probably associated with the polymorphic change in AgCl. Previous experience with the effect of pressure on the melting points would prepare one to anticipate such a high pressure stiffening, since at high pressures the order of melting points in the alkali series reverses, caesium having the highest melting point and lithium the lowest.

The one run which gave good values below 30,000 gave smooth values down to 5,000, exhibited the low pressure minimum in this neighborhood, and at the previously known lattice transition [12] from body centered to face centered cubic near 23,000 exhibited a discontinuity of resistance with the unusual increase of resistance already known. All three runs agreed qualitatively above 30,000 in showing a rapid rise to a sharp cusp within 1,000 kg/cm^2 of 55,000, followed by a smooth drop with marked upward curvature to 100,000. Because of its importance, readings were made with decreasing pressure in the same small steps as with increasing pressure and the same behavior found, namely a sharp cusp, rising to practically the same height as with increasing pressure. The pressure of the cusp with decreasing pressure was lower, however, by nearly 20,000 kg/cm^2. The mean pressure of the cusp with increasing and decreasing pressure varied in the three runs from 43,000 to 44,000 kg/cm^2, nearly the same as the pressure of the electronic transition, 45,000, previously found. One might be inclined to infer from this that the directly observed pressures with increasing and decreasing pressure differ by friction by the amount of this difference. This I believe would be a quite unjustified conclusion in view of the other evidence, for instance, the agreement of the known transition pressures for bismuth and thallium, the position of the minima for potassium and rubidium, and the fact that for caesium itself the lattice transition occurs at approximately the correct pressure. It seems to me that most of the difference at the electronic transition between increasing and decreasing pressure is to be ascribed to real effects — most transitions run only with appreciable transgression of the thermodynamic equilibrium values and the amount of transgression is greater the smaller the specimen. The situation is complicated here by the unknown effect of the non-hydrostatic stresses in displacing the thermodynamic transition.

The three runs were in rather good numerical agreement; the relative resistances at the cusp in terms of the resistance at 30,000 were 2.24, 2.23, and 2.11. The three runs were simply averaged. The best method of reduction to secure agreement with former values is not so simple. In

the first place the former values were not for the free metal, but for caesium in glass. The former values were first corrected for the glass, as had also been done for rubidium. At 20,000 this amounted to a correction on the proportional resistance of approximately 10 per cent. It was then considered how to correct to displace the cusp from 55,000, its present value, to 45,000 as given by former volume measurements as the location of the electronic transition. This seemed a hazardous undertaking, particularly in view of the probability that most of the 10,000 displacement is real, and I did not attempt it. The simple course was adopted of multiplying all changes of resistance from 20,000 as fiducial by that constant factor which would secure agreement between present and previous results in the common range 20,000 to 30,000, and letting the cusp fall as it would. The factor of correction was 1.35, smaller than for the other alkali metals.

The results so corrected are shown in Table I and in Figures 5 and 7. Any theoretical use made of these results will have to contemplate a possible shift of the pressure of the cusp of as much as 10,000 kg/cm^2 toward lower values, with such a consequent readjustment of the course of the entire curve as seems most plausible to the theoretician. The most surprising result of the present measurements is that the electronic transition is manifested as a *cusp* in the resistance, whereas the volume measurements gave it as a discontinuity in the volume (transition of the first kind). It is a task for the theoretician to discover whether so large a qualitative difference, extending over such a wide range of pressure, can be plausibly explained as an effect of internal strains in a substance as soft as this.

Copper. This was electrolytic copper of 99.9999 per cent purity, rolled to 0.001 inch thick and annealed at red heat in vacuum after forming. Four runs were made, with 10 per cent extreme variation of the resistance at 100,000 in terms of the resistance at 30,000 as fiducial. Below 30,000 the presently found changes of resistance are larger than the former values,[18] the correction factor running from 0.8 at the extrapolated zero to 0.9 at 40,000, extrapolated from the former results to 30,000. The correction above 40,000 was determined by a smooth free hand graphical extrapolation of the lower values to 100,000 in such a way as to approach unity asymptotically at 100,000. The precise method of extrapolating the correction factor is here of little importance; the resistance at 100,000, taking the observed values at their face value with no correction, is 0.856 at 100,000 against 0.866 given by the correction procedure outlined above The results are shown in Table II.

Silver. The material was old Kahlbaum "K" sheet stock. It was rolled to 0.001 inch thick and annealed to red heat in vacuum after forming. Four runs were made, with two different grades of carboloy, and two widths of specimen (0.010 and 0.020 inch). The extreme values for the propor-

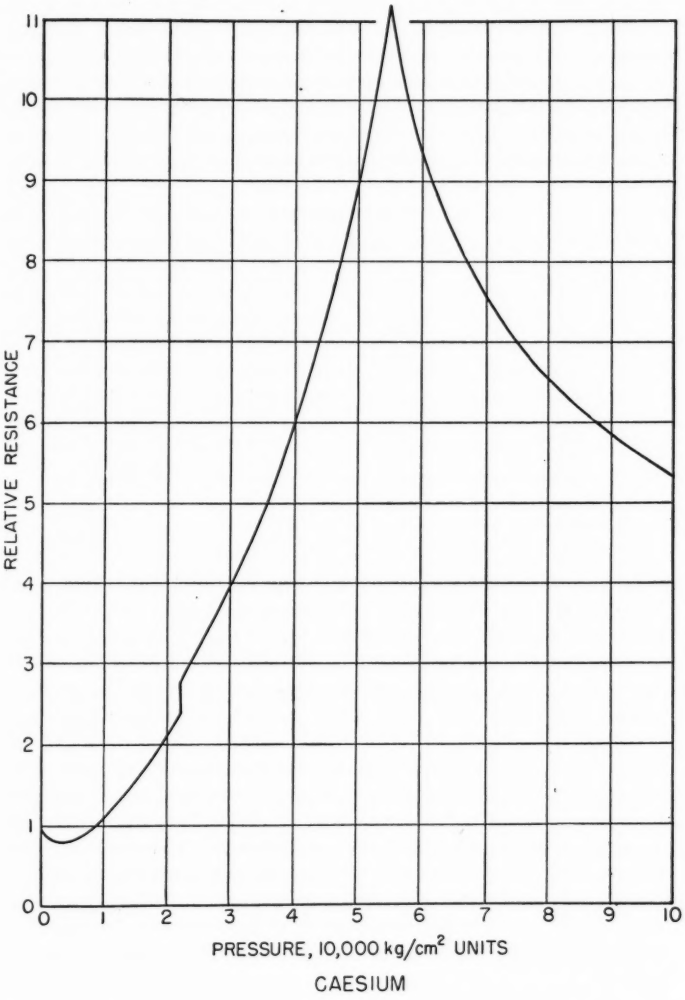

FIGURE 7. The relative resistance of caesium to 100,000 kg/cm^2.

tional change of resistance at 100,000, in terms of the resistance at 30,000 as fiducial, were 0.112 and 0.123. The four results were simply averaged. Compared with previous results [14] the changes of resistance were a few per cent less than those previously found. The difference as compared with copper is in the direction to be accounted for by the greater differential compressibility of silver. The correction between 30,000 and 100,000 was obtained by drawing a smooth free hand correction curve running to unity

TABLE II

Pressure kg/cm²	R/R₀		
	Copper	Silver	Gold
0	1.000	1.000	1.000
10,000	.981	.966	.971
20,000	.965	.936	.944
30,000	.949	.910	.919
40,000	.934	.885	.896
50,000	.920	.864	.874
60,000	.907	.846	.855
70,000	.895	.831	.840
80,000	.884	.819	.829
90,000	.875	.809	.821
100,000	.866	.802	.816

at 100,000. The maximum value of the correction on the change of resistance was 8 per cent. The results are shown in Table II.

Gold. The material was from Baker and Company, specified as their "highest purity" but with no analysis. It was rolled from 0.010 wire to 0.001 inch thickness and annealed. Four runs were made, with two grades of carboloy and in two widths, 0.010 and 0.020 inch. The proportional changes of resistance at 100,000 in terms of the resistance at 30,000 as fiducial were 0.117, 0.118, 0.116 and 0.101 for the four runs. These four results were simply averaged. Compared with previous results,[15] the present proportional changes of resistance are too large below 30,000 and somewhat too small at 40,000 (former result extrapolated). A smooth correction curve was drawn up to 100,000, with the limiting correction of unity at 100,000. The maximum correction on the change of resistance was 8 per cent. The precise correction procedure is of little moment; the resistance at 100,000 with no correction was 0.803 against 0.816 given as final in Table II.

Beryllium. The material I owe to the courtesy of the Brush Beryllium Company of Cleveland, who supplied me with a hot rolled sheet 0.004 inch thick. I had previously made unsuccessful attempts to machine a piece

of suitable dimensions from the cast rod on which my former measurements [16] had been made; the difficulty with this material is its mechanical hardness and its fragility in small thicknesses. The hot rolled sheet as furnished had a highly oxidized and mechanically irregular surface. It was filed or ground to thickness varying from 0.003 to 0.0015 inch for different specimens and widths varying from 0.020 to 0.030 inch. Three successful runs were made with two grades of carboloy. A fourth attempt failed because of a blow-out at 36,000 with increasing pressure, practically the only blow-out that has occurred under such conditions. The reason for this was that the carboloy block had been allowed to go too long without refiguring. Up to the point of blow-out the results on the fourth run agreed with the other three.

The observed decrement of proportional resistance at 100,000 in terms of the resistance at 20,000 as fiducial as found on the three runs was 0.085, 0.0917 and 0.0954; these results were simply averaged.

Although the resistance of beryllium had been previously measured [17] to 30,000, because of the presumptive difference between the former cast material and the present hot rolled sheet, the measurements to 30,000 were repeated, using the former apparatus. The mean temperature coefficient of resistance at atmospheric pressure between 0° and 25° for the present sheet material was 0.00591, against the former value for the casting of 0.00564. The present value, being somewhat higher, is presumptive of higher purity. It is to be noticed that both these temperature coefficients are higher than usual for a pure metal. The specific resistance at 0° at atmospheric pressure of the rolled sheet was 5.77×10^{-6}; it was not measured for the former specimen. At 25° the relation between pressure and $-\frac{1}{p}\frac{\Delta R}{R_o}$ for the sheet material was found to be linear, decreasing from 1.68×10^{-6} at atmospheric pressure to 1.52×10^{-6} at 30,000. The corresponding values for the former specimen decreased from 1.77×10^{-6} at atmospheric to 1.46×10^{-6} at 30,000, the drop being not linear, but at a faster rate at the lower pressures.

The present measurements to 100,000 give larger drops of resistance than do the measurements to 30,000, the ratio of the decrements from 20,000 as fiducial increasing from 0.550 at atmospheric pressure to 0.702 at 30,000. This ratio was smoothly extrapolated graphically to unity at 100,000, and the final values listed in Table III were so determined.

Calcium. The material was in lump form, obtained from Mackay in 1938. Since then it has been kept in a glass stoppered bottle under kerosene. There was a heavy crust over the surface, which could be readily scraped off, disclosing bright metal. Specimens for the present measurements were

prepared by cutting slivers from the block with a knife and squeezing to flatness between carboloy blocks. Since there was some tendency to crack during this squeezing, different specimens were prepared with different amounts of squeezing or filing, as the case might be, but with no discernible effect on the final result. The general order of dimensions of the specimens was 0.003 inch thick, 0.040 inch wide, and 0.18 inch long.

Four runs were made with two grades of carboloy. These runs appeared satisfactory in all cases, the readings being smooth over the entire range, except for two cases of very small disturbance above 90,000 presumably

TABLE III

Pressure kg/cm²	R/R₀			
	Beryllium	Calcium	Strontium	Barium
0	1.000	1.000	1.00	1.000
10,000	.984	1.107	1.56	.970
20,000	.969	1.258	2.38	1.008
30,000	.954	1.450	3.47	1.101
40,000	.941	1.686	4.58	1.200
50,000	.929	1.981	3.96[a]	1.340
60,000	.917	2.318	2.37	1.516
70,000	.906	2.710	1.89	1.744
80,000	.896	3.187	1.815	2.032[b] / 2.485
90,000	.884	3.753	1.805	2.549
100,000	.876	4.399	1.810	2.618

[a] Maximum of approximately 5.05 at 46,000.
[b] Transition at 80,000.

corresponding to the AgCl transition. Resistance increases under pressure; the four values for change of proportional resistance at 100,000 in terms of resistance at 30,000 as fiducial were 0.791, 0.775, 0.758 and 0.782. In spite, however, of the internally coherent results, the deviation from former measurements [18] to 30,000, was larger than usual. Below 30,000 the presently measured increases of resistance are smaller than before, and the factor in the range 20,000 to 30,000 was 1.712. Furthermore, this factor increases with pressure, being only 1.465 for the interval 0 to 10,000. The problem was how best to apply the correction. The procedure adopted before was clearly out of place, that is, to draw a correction curve approaching unity at the end of the range, for such a correction would pass through a maximum value and would introduce strange curvature into the course of the resistance curve for which there was no experimental plausibility. The simplest correction was adopted, namely to extrapolate linearly the correction factor which reduces the measurements in the former range to

30,000. The factor so determined rises to 2.66 at 100,000. The results so obtained are given in Table III and Figure 8. In all probability the resistance at the upper part of the range is markedly too high. Whatever the best method of correcting the results it must reproduce the qualitative features of a smoothly rising resistance, with no perceptible episode, and with continually increasing upward curvature.

Previous measurements of the volume of calcium [19] to 100,000 disclosed a polymorphic transition at 64,000 with a volume discontinuity of 1.3 per cent. No trace of this transition was found in the resistance measurements.

Strontium. This was obtained more than 15 years ago from Professor King of Syracuse, and is of demonstrated high purity. It has been kept sealed dry in glass. A thin powdery coat on the surface was rubbed off to give the bright metal. For the measurements it was squeezed between carboloy blocks under Dow Corning fluid 710 to the required thickness of 0.0025 inch. Squeezing under nujol was not successful because of sticking to the platens. Four runs were made with two grades of carboloy. In large features the runs were in agreement. Superficially the relation between pressure and resistance reminds one strongly of caesium. There is a rapid rise of resistance to about 45,000 kg/cm^2, followed by a pronounced drop. Unlike caesium, this drop presently flattens out, and in the last 10,000 kg/cm^2 turns into a slight rise, shown consistently by all four runs. Unlike caesium, the rise to 45,000 is not cusp-like, but is instead a sharp maximum, with definitely reversed curvature in the immediate neighborhood of the maximum on either side. The pressure of the maximum varied in the different runs through a range of about 2,000 kg/cm^2. The abruptness of the drop from the maximum varied from run to run, the major part of the drop being accomplished in from 15,000 to 20,000 kg/cm^2 beyond the maximum. On release of pressure the maximum was again reproduced, but with very great change in the qualitative features, the pressure being displaced from 46,000 to 5,000 and the rise to the maximum being only one third as much as with increasing pressure. This is unlike caesium, where the cusp was repeated with nearly the original height on release of pressure.

Compared with previous measurements,[20] the present change of resistance was less than before, but only about 25 per cent less, a fairly conservative effect. Furthermore, this factor did not vary with pressure, as it did for calcium. The final results were obtained by using a constant correction factor of 1.300, and are shown in Table III and Figure 7.

Previous measurements of the volume of strontium [21] to 100,000 have disclosed two polymorphic transitions: one at 25,000 kg/cm^2 with a volume decrement of 0.9 per cent, and one at 65,000 with volume decrement of

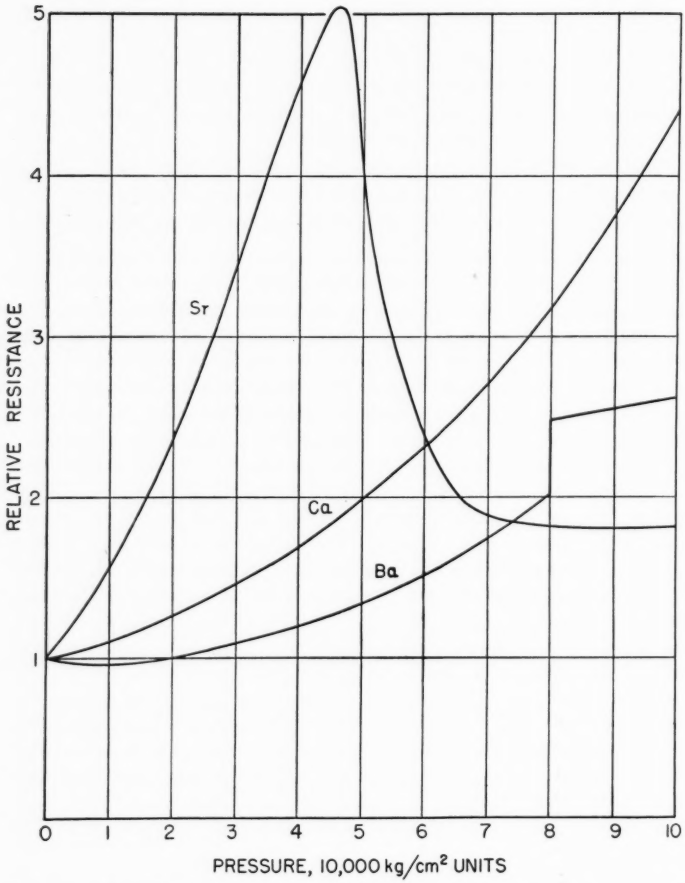

FIGURE 8. The relative resistances of calcium, strontium, and barium to 100,000 kg/cm².

0.8 per cent. No effect could be found during the present resistance measurements that could be ascribed to either of these transitions, either with increasing or decreasing pressure. Neither did the former resistance measurements to 30,000 in a true liquid disclose any irregularity that could be ascribed to the transition at 25,000. It is evident that the mechanisms

determining volume and resistance must have important points of difference. The maximum of resistance at 46,000 is strikingly large, with nothing corresponding in the volume.

Barium. This was the same material that had been used in the resistance measurements [22] to 30,000; it was originally obtained from Mackay and had been kept sealed under nujol since. It was in the form of extruded wire, and for these measurements was squeezed to a thickness of 0.0025 inch. The chemical activity of this in the air is so high that it was handled in the same vacuum arrangement as the alkali metals. Four runs were made with two grades of carboloy giving qualitatively consistent results. Resistance increases continually from the beginning with rapidly increasing upward curvature, until the process is abruptly terminated at 80,000, followed by a further moderate approximately linear rise from 80,000 to 100,000. The final uprush below 80,000 is so rapid that a first order transition seems the most probable state of affairs, and the final results are given on this basis. However, it must be kept in mind that a second order transition with discontinuity only in the tangent is not definitely ruled out. On release of pressure the rising curve was retraced with unusual fidelity almost in its entirety, except that the pressure of the discontinuity is displaced to 60,000.

Previous volume measurements [23] of barium to 100,000 have disclosed a polymorphic transition at 17,000 with volume discontinuity of 0.6 per cent, and another at 60,000 with volume discontinuity of 1.9 per cent. It is natural to associate the present discontinuity at 80,000 with the former transition at 60,000. Previous measurements of resistance to 30,000 disclosed a small discontinuity in the resistance which probably corresponds to the transition just mentioned at 17,000. The resistance change was so small, however, and showed so much capricious displacement and so great hysteresis between increasing and decreasing pressure that it was entirely smoothed over in the final tabulation of resistance. Distinct evidence of this same transition was found in the present work, and with the same properties of capriciousness and internal viscosity. Definite evidence for it was found twice with increasing pressure in the neighborhood of 40,000, and a third time it appeared to be merged with the approaching transition at higher pressure. The best evidence for it was with decreasing pressure, a definite discontinuity of resistance being observed at approximately the expected pressure on three possible occasions, the fourth observation being made impossible by a blow-out. However, the effect is so small and its location so uncertain that the former course was adopted of smoothing right across the transition in tabulating the final results.

The consistency of the various runs is indicated by the values of proportional resistance at 100,000 in terms of the value at 20,000 as fiducial.

These values were: 2.349, 2.352, 2.057, and 2.067. They were averaged for the final. Compared with previous results to 30,000 the increase of resistance is less than found before, which is the universal direction of discrepancy for metals with a positive coefficient. The best way of correcting to the former values is obscured by the minimum resistance at low pressure. The course was adopted of applying a constant correction factor of 1.323, this being the factor that produces agreement in the interval 20,000 to 30,000. The final values are shown in Table III and Figure 7. This table shows a slight upward curvature between 80,000 and 100,000. This is doubtful; it was demanded by the unadjusted average of the four runs, but two of the runs showed a very slight downward curvature. There was no evidence of disturbance by the transition of AgCl.

Magnesium. This was old single crystal stock which had been used in former measurements. It was rolled to a thickness of 0.002 inch with one intermediate annealing at 0.015 inch thickness. The edges of the rolled strip were frayed out, but the center appeared homogeneous. The specimens were cut with the length perpendicular to the direction of rolling, and widths varying from 0.013 to 0.039 inch were used. Four set-ups were made with two grades of carboloy. The changes of proportional resistance to 100,000 in terms of resistance at 30,000 as fiducial were: 0.0739, 0.0830, 0.0800, and 0.0789, with no apparent correlation with either grade of carboloy or dimensions of the specimen. The four results were averaged.

Compared with previous measurements[24] to 30,000 the present decrements of resistance were 40 per cent smaller. The discrepancy was approximately constant, showing no trend with pressure. The final values were therefore obtained by using a constant correction factor of 1.70. The final results are shown in Table IV. It is to be remembered that magnesium is hexagonal and that therefore anisotropy is a complicating factor. However, previous measurements have shown that the variation of both resistance and pressure coefficient of resistance in different directions is not important for this metal.

Zinc. This was old single crystal stock, from highly purified material which W. A. Zisman had prepared in this laboratory 25 years ago in connection with his measurements of contact potentials.[25] Zinc is markedly anisotropic, the compressibility along the axis being seven times as great as at right angles. The resistance, on the other hand, varies only about 4 per cent with orientation. At any rate, because of the unknown disorienting effect of non-hydrostatic pressure the significance of any results that might be obtained seemed somewhat obscure, and only two runs were made with this material instead of the usual four. One of these was made on a sliver worked out of the original single crystal, the length of the specimen being

along the cleavage plane. The other specimen was prepared so as to have as haphazard an orientation as possible by first preparing from the single crystal stock a wire of 0.006 inch diameter by hot extrusion, and then squeezing the wire flat to a thickness of 0.002 inch. The specimen parallel to the cleavage plane showed a drop of proportional resistance at 100,000, calculated from 30,000 as fiducial, of 0.181, while the corresponding change for the extruded and squeezed specimen was 0.151. The average was taken for the final results. In order to compare with previous results,[26] which were obtained on different orientations of the single crystal, it was necessary to average the former results for haphazard orientation.

TABLE IV

Pressure kg/cm^2	R/Ro			R/R$_{20}$
	Magnesium	Zinc	Cadmium	Mercury
0	1.000	1.000	1.000	
10,000	.953	.937	.927	
20,000	.916	.887	.872	1.000
30,000	.886	.847	.828	.895
40,000	.859	.812	.792	.803a .682
50,000	.837	.783	.762	.652
60,000	.817	.756	.736	.627
70,000	.800	.733	.713	.606
80,000	.786	.713	.693	.587
90,000	.776	.695	.675	.570
100,000	.767	.679	.658	.555

[a] Transition

In spite of the fact that the specific resistance in different directions differs by only 4 per cent, the pressure coefficient of resistance in the cleavage plane is more than twice as great as at right angles, a direction of deviation the opposite of what would be expected from the difference of compressibility. When so corrected, the present decrements of resistance are consistently less than the former ones, and furthermore the difference shows a consistent trend with pressure. The final correction was made by assuming a correction linear with pressure. The value of the factor is 1.182 at 30,000 and 1.427 at 100,000. The final results are shown in Table IV. The finally corrected proportional resistance at 100,000 is 0.679 against the value 0.740 which would have been obtained applying no correction whatever.

Cadmium. The material was spectroscopically pure cadmium, prepared by vacuum distillation which I owe to the courtesy of the New Jersey Zinc Company many years ago. For these measurements a small lump

was rolled to a thickness of 0.001 inch and used in two widths, 0.010 and 0.020 inch. Four runs were made with two grades of carboloy. These runs gave for the proportional change of resistance at 100,000, in terms of the resistance at 20,000 as fiducial, the values: 0.247, 0.235, 0.248, and 0.257. They were averaged for the final.

Previous measurements [27] have been made on the resistance of cadmium only to 12,000 kg/cm², on extruded wire. After those measurements had been made it was found [28] that cadmium exhibits a transition at 5,000 with rather special properties. The change of either volume or resistance at this transition is small, and furthermore is exhibited in measurable magnitude only by highly pure single crystal material. The transition is of that type in which the original crystal is not recovered on release of pressure, but the original single crystal becomes a multicrystal after an excursion back and forth through the transition. The exact significance of any results obtained with cadmium is therefore not plain, and this was the reason for not extending the former measurements to 30,000 along with all the other materials. However, the changes are small due to crystal orientation, and in view of the large changes now of interest in the range to 100,000 it appears that the decision not to measure to 30,000 was a counsel of perfection. Accordingly new measurements have now been made in the 30,000 apparatus with true hydrostatic pressure. The material was wire extruded from the same stock as that used above for the 100,000 measurements. The temperature coefficient between 0° and 25° was 0.00401, and the specific resistance at 0° at atmospheric pressure 6.4×10^{-6}. The results of the new measurements to 30,000 are shown in Table V, given in the same form as for the other metals recently measured over the same range.

Compared with the present measurements in the 100,000 apparatus the proportional changes of resistance in terms of the resistance at 20,000 as fiducial are somewhat larger, the reduction factor being 0.839 at 10,000 and 0.888 at 30,000. The correction factor used in the range 40,000 to 100,000 was obtained by smooth graphical extrapolation of these values to unity at 100,000. The values thus corrected are shown in Table IV.

Mercury. This is liquid below 13,000 kg/cm² at room temperature,[29] so that some special method of handling it is required. The difficulties of confining it in immediate contact with the AgCl and getting electrodes into it without leak seemed prohibitive. It was accordingly confined in a very thin flat platinum tube which was inserted into the cell like an ordinary solid specimen. A dummy run with the empty tube gave the contribution to the resistance by the platinum, from which the contribution of the mercury was calculated by the ordinary formula for two resistances in parallel. With the dimensions used, the resistance of the mercury alone varied from 3 to 4 times the total resistance; the relations become more

favorable at the higher pressures. The tube was formed from platinum foil specially rolled by Baker and Company to a thickness of 0.0003 inch. The particular piece of foil used for the tube had to be selected to avoid pin holes. It was welded into a flat tube over a form in a stainless steel clamp by heating the whole clamp to a dull red. Excessive temperature must be avoided or there will be sticking to the form or clamp; it was a surprise that so low a temperature would suffice. One end of the tube was sealed flat by the same method. The tube was then tested for soundness with moderate air pressure, sealing it with wax to the source of pressure.

TABLE V

RESISTANCE OF CADMIUM TO 30,000 KG/CM^2

Pressure kg/cm^2	$-\frac{1}{p}\frac{\Delta R}{R_o} \times 10^6$
0	8.55
5,000	7.89
10,000	7.32
15,000	6.84
20,000	6.40
25,000	6.05
30,000	5.72

Filling with mercury was then accomplished by several applications of moderate vacuum, the quantity of mercury controlled by inserting a displacing ramrod, and the open end of the tube sealed sufficiently for the purpose by folding over the open end of the tube on itself several times. The quantity of mercury was then determined by weighing, and the filled tube inserted into the cell in the usual way. The over-all width of the insert was about 0.040 inch and the thickness 0.004 inch.

The specimen thus prepared did not permit acceptable measurements on the liquid, even on the first application of pressure. Even more, after freezing had once taken place, no measurements were possible on release of pressure in the domain of the liquid because of rapid leak, often accompanied by short circuiting between the carboloy blocks by the escaped mercury, which permeated all parts of the assembly, including the pipestone retaining ring. Accordingly, immediately on assembly, pressure was raised rapidly, in a few seconds, to 23,000 kg/cm^2, well above the freezing pressure. Under these conditions freezing took place so rapidly that any escape of liquid was too small to be troublesome. Above 23,000 readings could be made at leisure in the regular way.

Because of the mechanical limitations it is obvious that one will have to

be content with less information here than for the usual solid specimen. There are a couple of points of sufficient interest to justify some effort to get even qualitative information. It is known that mercury has a second high pressure form,[30] the transition line with the ordinary form running from $-109°C$ at 10,000 kg/cm^2 to 23°C at 35,000. No measurements of the resistance of the high pressure modification have been previously made, and the present measurements should be capable of giving some information about it. The particular points of qualitative interest are: (a) the direction of the change of resistance at the transition, that is, does it follow the change of volume like most transitions, or is it like the few abnormal transitions, and (b) the sign of the pressure coefficient of the high pressure form.

Two runs were made to 100,000 which appeared fairly satisfactory in the light of internal evidence, and a third run in which the internal evidence indicated that too much of the mercury had escaped on the initial freezing. In addition, a number of abortive attempts at runs were made. The two runs agreed in the main qualitative features. As far as quantitative values go, it would seem that the best that can be done is to average the two runs, since there is no presumption as to which run is better, geometric rearrangement of the mercury within the platinum sheath affording opportunity for the measured effects to be either too large or too small. Both runs agreed in giving a sharp drop of resistance at the transition, which occurred at 40,000 at 26.5° with increasing pressure, or at a mean pressure with increasing and decreasing pressure at 34,000. The formerly determined transition pressure at this temperature was 36,000 kg/cm^2. The third discarded run confirmed the existence of a discontinuity in the same direction at the same pressure. The two good runs did not agree with respect to the amount of drop of resistance; in the one case the resistance of the high pressure form was 80 per cent of the resistance of the low pressure form at the transition, and in the other case, it was 89.1 per cent. The best that can be done is to average these, or 84.5 per cent. Both runs agreed in giving a marked drop in the pressure coefficient at the transition. The average results of the two runs in terms of the resistance at 20,000 taken as fiducial are given in Table IV. Compared with previous results[31] on the low pressure modification between 20,000 and 30,000 the present decrement of resistance is too small by a factor of 0.65. In view of the uncertainties introduced by the transition, no attempt was made to correct for this. The strong probability is that the resistance drops more rapidly at the high pressures than given by the table. The failure of agreement does not necessarily reflect on either the former or the present measurements since there is here a possible effect of anisotropy which would require elaborate study to evaluate.

High pressure mercury thus appears as having a normal negative pressure coefficient of resistance and a numerical value placing it among the softer and more compressible metals, as would be expected.

Aluminum. This was cut from a standard melting point sample of the Bureau of Standards. It was rolled to 0.001 inch thick, stamped to shape, and annealed in vacuum to 400°. Four runs were made, with two grades of carboloy and two widths, 0.010 and 0.020 inch. The proportional change of resistance at 100,000, in terms of the resistance at 30,000 as fiducial, varied from 0.132 to 0.142. The average was used in the final result. Compared with former measurements [32] to 30,000, the decrements of resistance are smaller, and show a consistent trend with pressure, the discrepancy being about 10 per cent at atmospheric pressure and 5 per cent at 50,000 (by extrapolation of the former results). A correction was therefore applied running linearly with pressure to zero at 100,000. The correction is less than usual, and the results should be accordingly more secure. The final results are shown in Table VI.

TABLE VI

Pressure kg/cm^2	R/R$_0$			
	Aluminum	Gallium	Indium	Thallium
0	1.000		1.000	1.000
10,000	.959		.891	.882
20,000	.923		.810	.799
30,000	.892	See	.746	.727
40,000	.865		.694	.665
50,000	.843		.650	.436[a]
60,000	.824	text	.610	.391
70,000	.808		.578	.352
80,000	.794		.548	.319
90,000	.782		.520	.290
100,000	.770		.493	.265

[a] Transition at 45,000. Resistances .639 and .460

Gallium. The material was recently obtained from Mackay. The melting point at atmospheric pressure is known to be 29.7° and the melting is of the ice type, so that the melting temperature is lowered by pressure. It is therefore liquid at room temperature over the lower end of the pressure range, and it was handled by the same technique as mercury in a platinum sheath. It is known from previous measurements [33] that the melting curve falls to a triple point at 12,050 kg/cm^2 and 2.4°C with a new high pressure form, the melting point of which rises with pressure. No experimental points have been determined on the melting curve of the high pressure modification, however, and it is known only as a short stretch in the im-

mediate neighborhood of the triple point obtained by thermodynamic calculation. The situation in the neighborhood of the triple point is complicated by the presence of an absolutely unstable form, with properties nearly the same as those of the stable form. Linear extrapolation of the melting curve of the stable form indicated melting at 25° at a pressure of 26,000 kg/cm^2.

The new information to be expected from the present experiment was therefore the approximate freezing pressure of the high pressure form at room temperature, the direction of resistance change on freezing to this form, and the pressure dependence of resistance of the high form up to 100,000.

Gallium is easier to handle than mercury at atmospheric pressure while assembling in the platinum sheath and the cell because it is solid. The nearness of the melting point, however, required that the tools be cooled and all the work of assembly was done on heavy blocks of chilled iron. Gallium has the property that it supports more subcooling than most metals, so that if it is once melted it is difficult to get the solid phase back again. This, combined with the higher freezing pressure at room temperature, made it more difficult to handle under pressure than mercury. Serious attempts were made to get information on the behavior of the liquid phase under pressure, but without success, there always being too much leak. Accordingly the same manipulation was necessary as with mercury, namely rapid freezing by sudden application of pressure. To be on the safe side, 45,000 was chosen as the initial pressure. This did indeed produce freezing, but only with appreciable leak, judging by the internal evidence. The escaped metal might form capricious short circuits between the carboloy blocks.

Four set-ups were made sufficiently promising to justify readings over the range to 100,000, and of these two were free from capricious shorts in the domain of stability of the solid and were used in the final calculations. In addition, several unsuccessful set-ups were made. Calculations were made as for mercury in terms of a dummy run with empty platinum tube. Above 40,000 resistance drops smoothly with increasing pressure. No previous measurements of any sort have been made on gallium above 50,000. The smoothness of the resistance indicates that there are no polymorphic transitions in the new range. In this respect gallium exhibits great poverty of behavior as compared with that other ice-type metal, bismuth, which has six polymorphic modifications below 100,000. Above 40,000 the resistance of solid gallium may be taken with sufficient approximation to be linear in pressure. Any slight curvature is in the normal direction. In terms of the resistance at 40,000 taken as unity the resistance at 100,000 given by the two runs was 0.855 and 0.886, average 0.870.

On release of pressure partial information was obtained on the relations at melting. Melting is accompanied by an increase of resistance, but by how much it would not be safe to estimate because of the disturbing effect of leak. The melting pressure on release could be shut within limits, 4,000 kg/cm^2 apart. The mean pressures of the three usable runs were 38,600, 34,200, and 38,600. There is some doubt about the pressure on release because of the irreversibility in the deformation of the pipestone, but on the other hand there is no overshooting of the melting curve. The pressures just quoted are sufficiently above the extrapolated melting pressure, 26,000, already mentioned, to make it fairly certain that the curvature of the melting curve of the high pressure modification is in the normal direction, that is, concave toward the pressure axis.

Previous measurements of the resistance of solid and liquid gallium [33] to 12,000 had shown that the resistance of the liquid is less than that of the ordinary atmospheric modification. The resistance of both the normal and the high pressure modifications of gallium therefore follows the direction of volume change through a phase change with the liquid. This is the normal direction.

Indium. This was from old Mackay stock, described as 99.9 per cent pure. It was squeezed to a thickness of 0.0035 inch and cut to widths varying from 0.027 to 0.037 inch. Four runs were made with two grades of carboloy. The drop of proportional resistance at 100,000, in terms of the resistance at 30,000 as fiducial was: 0.203, 0.215, 0.225, and 0.209. The simple average was taken. Compared with previous results [34] to 30,000 the present decrements are too small, the expected direction of discrepancy for a compressible metal arising from differential compressibility. The correction factor showed a trend with pressure. For the final values a correction factor was used increasing linearly with pressure from 1.27 at atmospheric pressure to 1.59 at 100,000. The final values of resistance are given in Table VI. The resistance at 100,000 is one half the initial value, and the relation between pressure and resistance shows marked curvature in the normal direction. This is not unexpected in a metal as soft and compressible as indium.

Thallium. This was from my old stock inherited from Professor T. W. Richards who had prepared it for his atomic weight determinations. It was squeezed to 0.003 inch thickness and cut to a width of 0.040 inch. Discoloration of a freshly cut surface in the air was rapid enough to demand filling with the vacuum technique used for the alkali metals. Four runs were made with two grades of carboloy. The proportional decrements of resistance at 100,000, in terms of resistance at 20,000 taken as unity, were: 0.483, 0.421, 0.434, and 0.422. These results were averaged. Thallium

is known to have a polymorphic transition [35] at 40,000 kg/cm² with volume change of 0.7 per cent. This transition was found in the present measurements at 45,000 with increasing pressure. It is more clean cut than most transitions. It always ran on reaching 45,000 and never at 41,000. It is accompanied by a drop of resistance of 28 per cent, larger than might have been anticipated in view of the smallness of the change of volume. On release of pressure the transition always ran at 28,000 and never at 32,000. It is to be remembered that the absolute pressure on release is uncertain; in the table the discontinuity of resistance is given at 45,000. This does not mean that 45,000 is now regarded as a better value for the transition pressure than the former 40,000 — it is merely that this value was given more directly by the present readings. The value of resistance tabulated at 45,000 for the low pressure modification doubtless applies to that modification in the superpressed condition.

The resistance of thallium had not been previously measured to 30,000. The reason was that thallium is not cubic, and I had hoped to get sometime a single crystal for measurement in the different orientations. However, in view of the large changes of resistance produced by the 100,000 kg/cm² of the present work the same remarks apply as to cadmium and special measurements were made of the resistance of thallium to 30,000 in the form of extruded wire and therefore unknown crystal orientation. The average temperature coefficient between 0° and 25° of the specimen measured to 30,000 was 0.00436, and the specific resistance at 0° 1.74×10^{-5}. The new results to 30,000 are shown in Table VII. Thallium has been previously measured [36] to 12,000. The decrement of resistance at 10,000 formerly found was 0.094 against 0.118 now. The former temperature coefficient of resistance was 0.00518.

The decrements of resistance given by the measurements to 100,000 were smaller than those from the 30,000 measurements, as is usually the case for soft highly compressible metals. The ratios did not vary consistently, however, being 0.718, 0.763, and 0.658 at atmospheric, 10,000 and 30,000 respectively, so that the best method of extrapolating the correction is in much doubt. The course adopted was to use a constant correction factor of 0.658 from 30,000 to 100,000, and the results shown in Table VI were so obtained. It must be recognized that the high pressure results are more in doubt than usual. There would seem to be no reasonable doubt, however, of the qualitative results that the resistance drops by a fairly large amount at the 45,000 transition, and that above 45,000 the resistance of the high pressure modification drops with a large coefficient.

Lanthanum. Lanthanum shows highly unusual phenomena in which it is unique. In all, ten runs were made to 100,000 on material from two different sources and with different treatments. Previously the electrical

resistance had been measured to 12,000 in 1927 [37] on presumably pure material and again in 1951 [38] on somewhat less pure material, and the compressibility has been measured [39] to 45,000 and to 100,000. The compression measurements showed a transition at 23,700 kg/cm^2 with fractional volume change of 0.0036. This transition did not appear in the resistance measurements to 30,000, which did, however, show so much hysteresis that it seemed desirable to tabulate the results with both increasing and decreasing pressure.

Of the ten present runs to 100,000, four were made on the same material obtained from Mackay on which the 1951 resistance measurements were made. After these measurements had been completed I was fortunate to

TABLE VII

RESISTANCE OF THALLIUM TO 30,000 KG/CM^2

Pressure kg/cm^2	$-\frac{1}{p}\frac{\Delta R}{R_o} \times 10^5$
0	1.400
5,000	1.276
10,000	1.180
15,000	1.098
20,000	1.025
25,000	0.960
30,000	0.910

obtain some highly purified material through the courtesy of Dr. F. H. Spedding of the Atomic Energy Commission. Two runs to 100,000 with this material gave results qualitatively similar to those with the other material, but there were minor differences between all six of these runs which were greater than to be expected. Qualitatively, the resistance passes through a stage of markedly accelerated decrease between 25,000 and 50,000, above which the rate of drop becomes less again. All these six specimens had been prepared by cutting small pieces from the original massive blocks and cold pressing these pieces between carboloy platens to the desired thickness. The material was therefore in a condition of considerable cold work, the effects of which, in view of experience with other materials and the comparative softness mechanically of lanthanum, were not anticipated to be of importance. At this stage shearing measurements were made on lanthanum in a new carboloy apparatus to 100,000. The shearing measurements showed no transition in the neighborhood of 25,000, and the only feature was an accelerated rise of shearing strength above 80,000. These shearing measurements yielded sheared discs of appropriate

dimensions, and the resistance measurements to 100,000 were repeated on a specimen cut from one of these discs. The results were strikingly different from those previously obtained, the accelerated drop of resistance being smeared out over a wide range. It thus appeared that the resistance of lanthanum is unusually sensitive to cold working, and the clue thus afforded was followed up. Three more runs were made to 100,000, the first on a specimen sawed and filed from the original massive block, the second on a strip filed from a wire extruded at dull red heat (it was assumed that the wire would self-anneal after the extruding because of the

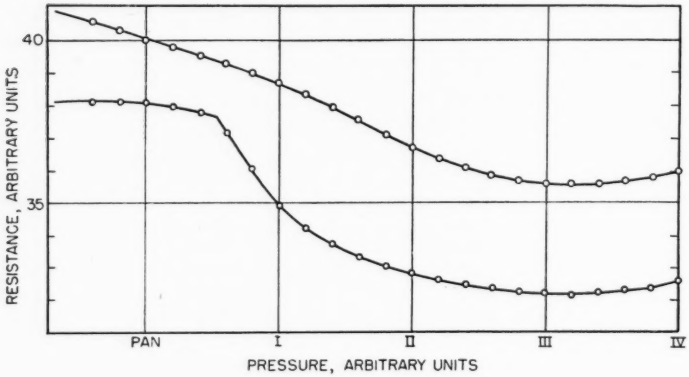

FIGURE 9. The resistances on an arbitrary scale to 100,000 kg/cm² of lanthanum in a severely cold-worked condition and annealed. There is no significance in the different origins for the two specimens.

high temperature), and the third on a specimen similar to the second except that it was annealed in vaccum at 500° for two hours and cooled with the furnace over night.

In Figure 9 are shown the directly measured resistances with increasing pressure to 100,000 of the heavily sheared material and of the sawed and filed specimen. The smearing out of the transition or whatever it is for the sheared specimen is striking.

The three runs on the non-squeezed material gave essentially the same results; these three runs were averaged for the final results. Resistance is very nearly constant up to 25,000, in two cases decreasing slightly and in the other passing through a flat maximum. Between 25,000 and 30,000 a drop begins with cusp-like rapidity. The pressure of the cusp varied from 26,000 to 29,000. Any actual discontinuity of resistance corresponding to

the previously found transition was too small to establish. The rapid drop of resistance presently flattens out with a point of inflection, and near 90,000 the resistance passes through a flat minimum, shown by all three runs.

The former measurements to 30,000 were now repeated with the new pure material in the form of annealed extruded wire. The average temperature coefficient of resistance at atmospheric pressure between 0° and 25° was 0.00218. This is to be compared with my previous values 0.00218 and 0.00213, the latter for the purer material. There would not seem to be much room for doubt that the temperature coefficient of pure lanthanum is only about one half the value to be expected for most pure metals. The specific resistance at atmospheric pressure at 0° was 6.24×10^{-5}. This is to be compared with the previous values 6.13 and 5.76×10^{-5}, the latter for the purer material. There seems no consistent variation of specific resistance with presumptive purity.

TABLE VIII

RESISTANCE OF THREE RARE EARTH METALS TO 30,000 KG/CM^2

Pressure kg/cm^2	R/R$_0$			
	Lanthanum			
	Increasing	Decreasing	Praseodymium	Neodymium
0	1.000	1.000	1.0000	1.0000
5,000	.991	.983	.9973	.9910
10,000	.983	.956	.9956	.9850
15,000	.975	.927	.9955	.9756
20,000	.965	.916	.9959	.9694
25,000	.935	.910	.9969	.9640
30,000	.894		.9980	.9600

The resistance measurements to 30,000 showed the beginning of the same effects which were found to 100,000. Between 20,000 and 30,000 a rapidly accelerated drop of resistance begins, with no slackening of this drop below 30,000. On reversal of pressure there is great hysteresis, and rapid recovery of resistance does not begin until 15,000. The resistance as a function of pressure with increasing and decreasing pressure to 30,000 is shown in Table VIII. At the higher pressures the results do not agree at all with the 1951 values, the hysteresis being much more pronounced, but the slope at atmospheric pressure, both with increasing and decreasing pressure, agrees rather closely with 1951. It would appear that the delayed internal change which is responsible for the rapid drop of resistance has not begun at atmospheric pressure with increasing pressure, and has been nearly completely wiped out at atmospheric pressure on release.

No plausible scheme presented itself for correcting the results to 100,000 so as to secure agreement with the new results to 30,000. The transition, being spread over a wide range, is sensitive to the width of the range, and the interval from 10,000 to 30,000, which would have to be basic to any correction that might be determined, is in a sensitive part of this range. Accordingly the average of the three runs to 100,000 are presented without correction as the final results in Table IX and Figure 10. It is to be expected that these are uncertain by something of the order of the correction which has been used for other more normal metals of the same compressibility. Qualitatively, a rapidly accelerated drop of resistance begins somewhere between 25,000 and 30,000 (corresponding to the transition

TABLE IX

Pressure kg/cm²	R/R₀			
	Lanthanum	Cerium	Praseodymium	Neodymium
0	1.0000	1.000	1.0000	1.0000
10,000	.9997	.548	.9956	.9850
20,000	.9978	.506	.9959	.9694
30,000	.9759	.487	.9980	.9600
40,000	.903	.477	1.0007	.9550
50,000	.867	.469	.9943	.9527
60,000	.849	.4620	.9312	.9525
70,000	.8398	.4625	.8889	.9525
80,000	.8362	.4711	.8799	.9544
90,000	.8368	.4857	.8819	.9572
100,000	.842	.4817a	.8902	.9623

[a] Cusp at 91,000, resistance .4871

previously found in the volume measurements) the drop slowing down and presently reversing in direction. The presumption is that the new modification which gradually appears over a wide range has completely supplanted the original modification in the neighborhood of 90,000. This new modification in the pure state has a smaller resistance than the original, but a positive pressure coefficient of resistance. On release of pressure the reverse transition apparently does not begin to run until the pressure of the cusp has been reached or passed, so that in the entire range from 100,000 to less than 25,000 with decreasing pressure resistance is decreasing, which means a positive pressure coefficient. As already explained, in general the readings with decreasing pressure have not been used, the pressure being uncertain, but all three runs agreed in the features just described and there would seem no room for doubt that it is qualitatively correct. The total drop of resistance on lowering pressure from 100,000 to 25,000 is of the order of 2 or 3 per cent.

Cerium. This material was specially prepared by the Atomic Energy Commission for high purity; it was from the same batch as previously used [40] for measurements to 30,000. The specimens were cut to a width of 0.020 inch from sheet squeezed to a thickness of 0.00027 inch from a nodule cut from the original lump with a knife. There was no evidence of any such effects of mechanical strains as had been shown by lanthanum. In fact, previous experience during the measurements to 30,000 had shown no perceptible effect of complicated annealing procedures.

Four runs were made with qualitatively concordant results. There is

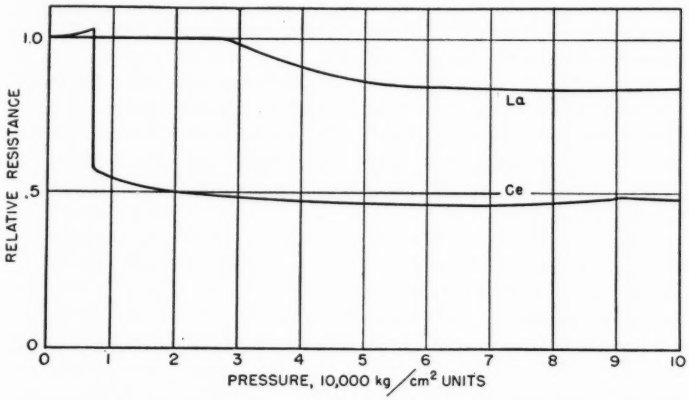

FIGURE 10. The relative resistances to 100,000 kg/cm^2 of lanthanum and cerium.

in the first place the large drop to approximately half the initial resistance at the known transition at 7,000. The curve continues after the abrupt drop with marked upward curvature. This curvature persists, leading to a minimum near 65,000. The rise with upward curvature now continues until terminated abruptly by an obtuse cusp at 91,000, beyond which resistance drops to 100,000. Expressed in terms of the resistance at 20,000 as unity, the drop in resistance from 20,000 to the minimum varied from 7 to 10 per cent, and the total drop from 20,000 to 100,000 from 3.6 to 6.0 per cent. The four results were averaged. Compared with previous measurements in the range 20,000 to 30,000 the present average resistance decrement is larger by 10 per cent. Present results were corrected to agree with the former ones by applying a correction of 10 per cent to the resistance changes from 20,000 uniformly over the entire pressure range.

The final results are shown in Table IX and Figure 9.

Praseodymium. Eight runs were made to 100,000, four on material from Mackay previously measured [41] to 30,000, and four on new material of high purity which I owe to Dr. Spedding of the Atomic Energy Commission. The measurements to 30,000 with true hydrostatic pressure were also repeated with the new material. In large qualitative features praseodymium is strongly reminiscent of lanthanum in that there is a region of accelerated decrease of resistance followed by an upturn. The impurer material shows qualitatively the same effects, except smeared out. There is also some sensitiveness to cold working, although not to nearly as great an extent as shown by lanthanum. The transition starts at a higher pressure and not with so sharp a cusp for the cold worked material. In the final results the average of the last two runs was taken, these being the only runs for which the material was free from all cold work.

The two sets of measurements to 30,000 show a qualitative difference. Formerly, with the less pure material, the resistance decreased over the entire range in a quite normal way. The resistance of the purer material decreases to a minimum near 15,000 and at higher pressures increases. A similar low pressure minimum was shown by one of the two finally retained runs to 100,000, but not by the other, which increased from the start. The average temperature coefficient of resistance at atmospheric pressure between 0° and 25° of the new material was 0.00171 and the specific resistance at atmospheric pressure and 0° 7.37×10^{-5}. For two previous specimens temperature coefficients of 0.00161 and 0.00165 and specific resistances of 7.39 and 6.9×10^{-5} have been obtained. As in the case of lanthanum there can be little doubt that the temperature coefficient is materially less than for most pure metals. The resistance measurements to 30,000 went smoothly, with no trace of hysteresis. The results are given in Table VIII.

The average of the two runs to 100,000 on strain free pure material (one sawed and filed from the block and the other filed from hot extruded wire) are given in Table IX. In this table the results for the first 30,000 kg/cm^2 were lifted directly from the new measurements over this range. Between 20,000 and 30,000 the average decrement of resistance from the 100,000 measurements was 0.0019 against 0.0021 from the 30,000 measurements. The agreement is unusually good and may be taken to justify the direct use of the 100,000 values at higher pressures without attempt at correction. The drop of resistance does not begin with quite cusp-like abruptness, but there is perceptible rounding. If the curve above and below is extrapolated to a cusp, the pressure of the cusp, that is the pressure at which the internal change begins, has the identical value for the two runs, 51,200 kg/cm^2. The fact that the run to 30,000 gave no hysteresis would indicate that no trace of this change has begun at pressures below

30,000. Compared with strain-free material, the two runs on presumably strained material differed in that the onset of the transition was displaced to a pressure about 7,000 kg/cm^2 higher. At the top, 100,000, the changes of resistance of both strained and strain-free material were practically identical. The nature of the new form that emerges after pressure passes through the transition zone is similar to the corresponding form of lanthanum in that its resistance increases under pressure. With decrease of pressure from 100,000 resistance decreases continually at a somewhat decreasing rate (that is, the curve of resistance against pressure is concave upward as is normal) until a pressure of 25,000 is reached, when the reverse transition begins and proceeds rapidly. It is to be noted that unlike lanthanum, the volume measurements [42] had given no hint of a transition in the neighborhood of the cusp. It is to be remarked, however, that the cusp for lanthanum being at a lower pressure the volume measurements were made with a considerably more sensitive apparatus than was used for praseodymium.

Neodymium. The history of the measurements on this is much the same as that of praseodymium. Eight runs were made to 100,000, four on material from Mackay, the same as used in recently published results [43] to 30,000 and four on high purity material which I again owe to the courtesy of Dr. Spedding of the Atomic Energy Commission. In addition, the new material was measured at 30,000. In general the results are not like either lanthanum or praseodymium, there being no evidence of internal change, but the effect of pressure on resistance is unusually small.

The results of the new measurements over the 30,000 range are given in Table VIII. There is definite hysteresis, which is averaged out in the table. The average temperature coefficient between 0° and 25° was 0.00164, and the specific resistance at atmospheric pressure at 0° 7.18×10^{-5}. These figures are to be compared with temperature coefficients of 0.00080 for the material measured many years ago [37] and 0.00127 for the recently measured material, the specific resistance of which was 8.05×10^{-5}. It is probable from the wider spread of the figures compared with the corresponding figures for lanthanum and praseodymium that impurity plays a more important part in the behavior of neodymium than of the two others. Again we have a rare earth metal with temperature coefficient markedly less than that of most pure metals. Neodymium is mechanically harder than the two others and much more subject to splintering when cold pressed. It is probable that this effect was responsible for the wide divergence between the results with the two grades of material when measured to 100,000. Three runs on the impurer material, formed by cold pressing, gave large decreases of resistance to 100,000, running to over 20

per cent. A fourth specimen filed from the hot extruded wire gave a drop of only 3 per cent. The difference was ascribed to the closing of cracks in the cold pressed specimens. After these runs, four runs were made to 100,000 on the pure Atomic Energy Commission material, the specimens having been treated as had those of lanthanum and praseodymium (sawing and filing and hot extrusion) to avoid the effects of cold work. The runs agreed in giving much smaller effects than the other material. Three of the four gave a definite minimum and the fourth was apparently approaching a flat minimum. In view of the smallness of the effect the four runs were averaged. Compared with the runs to 30,000 the change of resistance between 20,000 and 30,000 was only one third as much. Since the whole change of resistance of this material is within the possible limits due to the distortion of the carboloy, the only course seemed to be to correct the average results to 100,000 by multiplying the changes of resistance by the constant correction factor 3, and the results so obtained are given in Table IX. There is evidently much doubt with regard to the absolute values of the change of resistance, but I think the qualitative feature of a minimum resistance may be accepted.

Titanium. The material was from the same length of wire as used in recent measurements of resistance to 30,000. It was prepared by the Remington Arms Company under license from Dupont. For these measurements it was rolled to a thickness of 0.003 from 0.0167 inch wire. Previous experience had shown no effect of annealing, and the specimens were not further annealed after rolling. The width was about 0.035 inch.

Four runs were made with two grades of carboloy. The decrements of resistance from 30,000 to 100,000, taken in terms of the resistance at 30,000 as fiducial, varied from 0.050 to 0.058. The average was used. The present decrements of resistance are larger than before [44] in the range up to 30,000 and the ratios show an approximately linear trend with pressure. The present results were corrected to agree with the former ones to 30,000 by a correction factor rising linearly with pressure from 0.74 at atmospheric pressure to 1.00 at 100,000. The final results are shown in Table X. There is no special feature.

Zirconium. Two batches of material were used and two runs were made to 100,000 on each. The first two runs were made on rolled strip obtained from Mackay. The resistance decreases with normal upward curvature to the vicinity of 70,000, where the curve begins to turn over and continues with increasing downward curvature to 100,000. The second set was made with material obtained from the Philips works in Eindhoven a number of years ago which had been used in previous measurements of compressibility and pressure effect on resistance.[45] It had been prepared by vacuum dis-

tillation of one of the salts, and was presumably of high purity. The behavior of this purer material was only qualitatively reminiscent of that of the impurer. Resistance drops with normal upward curvature to nearly 80,000, where a precipitous drop begins, which is terminated before 100,000 by the curve turning and resuming approximately its original course. It would seem that this material experiences a polymorphic transition near 80,000, the effect of which was largely obscured in the impurer sample. This probably means that the impurity dissolves in both the low and high pressure lattices, something which does not always occur. Previous measurements of volume to 100,000 disclosed no transition.

TABLE X

Pressure kg/cm^2	R/Ro		
	Titanium	Zirconium	Thorium
0	1.000	1.0000	1.000
10,000	.989	.9977	.966
20,000	.979	.9954	.937
30,000	.970	.9933	.912
40,000	.961	9914	.892
50,000	.953	.9894	.876
60,000	.945	.9874	.862
70,000	.938	.9856	.850
80,000	.931	.9836	.840
90,000	.924	a	.831
100,000	.916		.821

[a] Transition above 80,000, with 16–17% drop of resistance

The absolute value of the pressure effect for this substance is unusually small; the present uncorrected measurements give a drop of resistance in the first 30,000 kg/cm^2 of less than 2 per cent and the former measurements of less than 1 per cent. The ratios of these small changes were plotted against pressure and a straight line drawn, giving a correction factor running from about 0.4 at atmospheric pressure to about 0.8 at 80,000. The values so corrected are shown in Table X. Considerable percentage error may be expected in the fractional changes of resistance. No attempt was made to give exact values beyond the transition or even at the transition itself. Approximate figures for the transition are indicated in the table. It is probable that the pressure coefficient of the high pressure modification is also negative, but no numerical estimate is justified.

Thorium. This was high purity material prepared by the Atomic Energy Commission, which I owe to the courtesy of Professor Bainbridge, who had obtained it from Dr. Spedding. It was in sheet form, 0.0009 inch thick

and was used in a width of 0.040 inch. Four runs were made with two grades of carboloy. The individual runs showed rather more variation than usual, the values for the decrease of resistance at 100,000 in terms of resistance at 30,000 as unity being: 0.125, 0.093, 0.084, and 0.101. The average was used.

The resistance of thorium has been previously measured[46] only to 12,000 on presumably less pure material. Accordingly new measurements were now made to 30,000. The specimen was a narrow strip cut from the same sheet as that of the 100,000 measurements; the four leads were spot welded in position. The average temperature coefficient at atmospheric pressure between 0° and 25° was 0.00275, and the specific resistance at 0° 2.67×10^{-5}. The temperature coefficient of the former material was 0.00239. The temperature coefficient indicates higher presumptive purity in the present specimen. The resistance measurements to 30,000 ran smoothly, with no hysteresis. The initial pressure coefficient is about 23 per cent greater than on the former material to 12,000. Within experimental error resistance is a second degree function of pressure, that is, $-\frac{1}{p}\frac{\Delta R}{R_o}$ is linear with pressure, decreasing from 3.610×10^{-6} at atmospheric pressure to 2.926×10^{-6} at 30,000, making the net decrease of resistance at 30,000 8.78 per cent.

The average of the four runs to 100,000 gave changes of resistance in the first 30,000 agreeing with the above within 2 per cent or better. The directly measured values were therefore used without correction, and these are the final values shown in Table X.

Carbon (Graphite). This was single crystal Ceylon graphite which I owed to the courtesy of Sir K. Krishnan a number of years ago. Specimens were prepared from cleavage sheets with length in the cleavage face of thickness 0.004 inch, width 0.080 inch, and the usual length 0.18 inch. There was considerable variation in the apparent perfection of the material. The most favorable appearing piece was selected and two specimens cut from it as closely contiguous as possible. The over-all results on these two specimens were nearly the same, the proportional decrements of resistance at 100,000 in terms of the initial resistance at atmospheric pressure as unity being 0.229 and 0.241. In spite of this gross agreement there were marked qualitative differences, the one specimen showing a shallow minimum at 14,000 followed by a flat maximum at 28,000, while the other showed only a minor interruption in its smooth course in this whole neighborhood. In view of the nature of the material it did not seem worth while to accumulate measurements, and only two runs were made. The average of the two is shown in Table XI. The abnormal downward

curvature at high pressures was shown by both specimens, as was also the high initial rate of drop up to 20,000. The near minimum and maximum between 20,000 and 30,000 was contributed by only one specimen. There are no previous measurements of the effect of pressure for comparison, the only previous measurements [47] having been made on Acheson graphite, which is not comparable because of its great porosity, to mention only one reason. Paradoxically the resistance of Acheson graphite was found to increase by a few per cent up to 12,000.

Some indication of the character of the present graphite may be obtained from its specific resistance. Rough values calculated for the specific resistances of the two specimens from the initial resistance and the dimensions

TABLE XI

Pressure kg/cm^2	R/Ro				
	Ceylon Graphite	Silicon	Germanium	Tin	Lead
0	1.000			1.000	1.000
10,000	.949			.910	.873
20,000	.911	See	See	.837	.779
30,000	.904			.775	.704
40,000	.893	Text	Text	.724	.647
50,000	.870			.683	.603
60,000	.852			.647	.570
70,000	.833			618	.543
80,000	.813			592	.521
90,000	.790			.569	.502
100,000	.765			.548	.487

were 116 and 109 $\times$ 10^{-6} ohm cm at room temperature. These figures may be too high by a few per cent because of electrode resistance, for which no correction was made. These specific resistances are to be compared with the value 39 $\times$ 10^{-6} given in International Critical Tables for "single crystals" material, orientation not specified.

Silicon. This material is a non-metal, is mechanically very brittle, and electrically is a semi-conductor. The resistance is supposed to be sensitive to "dislocations" mechanically produced. It would therefore be expected that any resistance measurements under pressure would be affected by the non-hydrostatic character of the stress more importantly than the metals of this paper. This did indeed prove to be the case; in fact the runs proved to be so difficult to interpret that only a few runs were made. There were, however, certain qualitative features that probably are of significance, and the results will be described sufficiently to indicate what these were.

The same high purity material was used, originally obtained from the

Bell Telephone Laboratories, that was used in recently published measurements to 30,000 under true hydrostatic pressure.[48]

The high specific resistance of this material suggests a modification of the method of mounting the specimen. Considerable effort was made to use the specimen in the form of a single button at the center of the AgCl cell, reaching through the cell into contact with the carboloy blocks on either side. It proved necessary to use amalgamated copper electrodes to regularize the contact, and when this was done there was always short circuiting between the blocks by way of copper squeezed into the crack between the specimen and AgCl. It was accordingly necessary to return to the use of a bar-shaped specimen in the AgCl sandwich. This meant initial resistances of the order of a few thousand ohms, and this meant a complete rearrangement of the electrical circuits. The details need not be given.

One run was made with p-type silicon. Formerly, up to 30,000, it was found that the resistance increased through a maximum and was decreasing over the last 10,000 kg/cm^2. On release of pressure there was hysteresis of two thirds the maximum effect. The entire range of resistance change was confined to 20 per cent. The new measurements gave irregular results, as usual, at low pressure, but from 10,000 to 36,000 a nearly linear decrease of specific resistance from 4.3 to 3.5 ohm cm. At 36,000 there was an abrupt drop to 2.3 ohm cm, followed by a further gradual drop to a minimum of 1.9 at 60,000, followed by a smooth rise to 3.3 at 100,000. On release the deep minimum was confirmed as also the rise at lower pressures with an abruptness suggesting some kind of transition.

Two runs were made with n-type silicon. Previous measurements to 30,000 had given an approximately linear decrease of resistance to about 50 per cent initial, with moderate hysteresis on release. In the present measurements both specimens gave an initial rapid drop of resistance, but this continued to only 10,000 kg/cm^2. Here a rise began by a factor of several fold for both specimens, but in the range 10,000 to 30,000 the details exhibited by the two specimens differed greatly. From 30,000 up to 100,000 both specimens agreed in a smooth decrease, with only minor interruptions of regularity, to a value at 100,000 approximately one third that at 30,000. On release, the episode of rapid rise from the high pressure side was confirmed. In spite of the rough qualitative agreement of the runs with the two specimens, which were cut from contiguous parts of the same piece, there was no agreement at all on the absolute values of specific resistance. Under 100,000 kg/cm^2 the specific resistance of one specimen was 0.11 ohm cm and of the other 7.6. The initial resistance at atmospheric pressure was 3.9 ohm cm. Strains and mechanical imperfections must be playing a preponderant role.

Germanium. This is a brittle semi-conductor and the same remarks apply as to silicon. Two runs were made, one on n-type and one on p-type. The method of mounting the specimens was the same as for all the other substances, as the inner layer in the AgCl sandwich. The electrical connections were the same as for silicon, demanded by the high resistance. The identical material was used as in recently published results [49] to 30,000. Fairly reproducible results were obtained with germanium; it was recognized by the Bell Telephone Laboratories that their germanium was more satisfactory than their (or anyone else's) silicon.

The previous measurements of n-type germanium up to 30,000 gave a moderate rise of resistance, by about 25 per cent up to 15,000, where there was a rapid upturn in the rate of rise, which at 30,000 amounted to a four fold increase of initial resistance. The initial specific resistance of the specimen of n-type germanium measured to 100,000, obtained by extrapolation to atmospheric pressure, was 18.7 ohm cm, in practically perfect agreement with the value 19 of the Bell Laboratory. The initial effect of pressure up to 7,000 was a decrease of resistance of 19 per cent, followed by a rapid upswing to a sharp maximum at 50,000 at double the initial resistance, followed by a smooth drop to 30 per cent more, at 100,000, than the initial resistance at atmospheric pressure. It would appear that these new results are not inconsistent with the previous ones to 30,000 if one takes seriously the suggestion that dislocations produced by strains in this material result in a decrease of resistance. The initial drop to 7,000 would then be ascribed to this effect. At 7,000 the natural rise takes over, but the dislocation effect persists and accounts for the rise to only double initial resistance instead of to 4.5 fold and more. The new feature contributed by the present measurements and which would seem to be qualitatively real, is the maximum at 50,000 and the rapid drop of resistance beyond it.

Previous measurements on p-type germanium to 30,000 gave an approximately linear drop of resistance of 6 per cent, with minor hysteresis which tended to vanish on repetition of the pressure cycle. The present measurements also gave a smooth decrease, except for an initial disturbance of no probable significance, amounting to 15 per cent at 30,000, and continuing to 82,000, where the drop is by 33 per cent. At 82,000 there is a minimum, beyond which resistance rises by 6.5 per cent to 100,000. The specific resistance of this specimen at atmospheric pressure was approximately 10 ohm cm, against the value 3.35 given by the Bell Telephone Laboratory.

Tin. The material was old Kahlbaum "K" stock. It was squeezed to a thickness of 0.001 inch and used in two widths, 0.010 and 0.020 inch. Four runs were made with two grades of carboloy. The proportional

changes of resistance at 100,000 in terms of resistance at 30,000 as fiducial were: 0.246, 0.246, 0.204 and 0.171. The two latter and lower values were obtained with grade 883 carboloy and the two others with grade 905. It does not appear whether the difference is significant — probably not. The four results were simply averaged. Compared with previous measurements [50] to 30,000, extrapolated to 50,000, the present decrements of resistance are too small. The ratio is nearly independent of pressure, and in making correction the present resistance changes were multiplied by the constant correction factor 1.35. The final result is given in Table XI. Resistance drops smoothly by a large amount; a large effect would be expected in so soft and compressible a metal.

Lead. This was of 99.9999 per cent purity, the same as has been used in a number of my previous measurements. It was squeezed to 0.001 inch thickness and used in widths of 0.010 and 0.020 inch. Four runs were made with two grades of carboloy. The proportional change of resistance at 100,000 in terms of the resistance at 30,000 as fiducial, given by the four runs was: 0.314, 0.299, 0.318, and 0.311. The results were averaged. Compared with previous measurements [51] to 30,000 the decrements of resistance now obtained are smaller than before. In the range of actual measurement, that is up to 30,000, the ratio between present and former decrements decreases approximately linearly with pressure and heads for the value 1 and 100,000. Accordingly a correction factor was used dropping linearly with pressure from 1.25 at atmospheric pressure to 1.00 at 100,000. It is to be noticed that if the former results are extrapolated beyond 30,000 by assuming constant second differences there will be no agreement, the extrapolated results indicating a minimum in the neighborhood of 60,000 for which there is no experimental evidence. This indicates the caution necessary in inferring the existence of any unusual feature by extrapolation. The final results are shown in Table XI. At 100,000 the resistance drops to 0.49 initial, an effect a few per cent greater than for tin.

Vanadium. It is only recently that this material has been available in pure form. I owe my specimens to the courtesy of the Research Laboratory of the General Electric Company at Schenectady. Material was supplied which had been prepared by two different methods. One was "calcium reduced vanadium." This was furnished in the form of a smooth rolled strip 0.004 inch thick and 0.5 inch wide. The analysis in weight per cent was: C $\sim$ 0.20, Fe $<$ 0.01, Si $<$ 0.01, Ca $<$ 0.01, O_2 0.03 to 0.05, $H_2 \sim$ 0.002, $N_2 \sim$ 0.01 to 0.03. The second material was "hot wire deposited vanadium". It evidently had been stripped from the hot wire and rolled, but the rolling left it in very irregular shape with longitudinal

cracks and curls and badly frayed edges. The central portion appeared homogeneous. The analysis of this was: Fe 0.01 to 0.015, Al $<$ 0.005, Si 0.01, Cr $<$ 0.005, Mn $<$ 0.005, Mo n.d., W n.d., Ni n.d., Ca tr, Mg tr, Cu 0.027 to 0.050, H_2 0.0004 to 0.0013, N_2 $<$ 0.004 to 0.008. Two runs were made, one on each grade, with a softer grade of carboloy, #779, than used in most of this work. Resistance decreased to 100,000 smoothly, with no episode of any kind. The proportional change of resistance at 100,000, in terms of the resistance at 20,000 as fiducial, was 0.1064 for the hot wire deposited material and 0.0799 for the calcium reduced.

A strip cut from the calcium reduced material was measured to 30,000. Its average temperature coefficient between 0° and 25° was 0.00366, and

TABLE XII

Pressure kg/cm^2	R/R$_o$		
	Vanadium	Columbium	Tantalum
0	1.000	1.000	1.000
10,000	.984	.986	.984
20,000	.969	.973	.968
30,000	.954	.961	.954
40,000	.941	.950	.941
50,000	.929	.938	.929
60,000	.916	.928	.918
70,000	.906	.918	.908
80,000	.895	.909	.898
90,000	.885	.901	.890
100,000	.878	.894	.882

the specific resistance at atmospheric pressure at 0° 2.09×10^{-5}. The relation between pressure and resistance is sensibly of the second degree in pressure up to 30,000. The value of $-\frac{1}{p}\frac{\Delta R}{R_o}$ drops linearly with pressure from 1.660×10^{-6} at atmospheric pressure to 1.524 at 30,000. Below 15,000 there are slight deviations from the regularity of the relation, with some hysteresis, which, however, is probably too small to be significant.

The resistance decrements given by the mean of the two runs to 100,000 were larger than those given by the measurements to 30,000, the ratio varying from 0.68 at atmospheric pressure to 0.82 at 30,000. This factor was extrapolated to the value unity at 100,000 by free hand graphical construction, and the values obtained with the correction so determined are given as the final values in Table XII. Vanadium seems normal in every way in its behavior to 100,000.

Columbium. This was laboratory stock from the Fansteel Company. It was in sheet form 0.0035 inch thick and was rolled to 0.0012 inch thick and annealed to red heat in vacuum. Four runs were made with two grades of carboloy, and with widths varying from 0.017 to 0.022 inch. The proportional changes of resistance at 100,000 in terms of resistance at 30,000 as fiducial varied from 0.067 to 0.082. The average was used. Compared with previous measurements [52] to 30,000 the present changes of resistance are too large. The reduction factor varies linearly from 0.68 at atmospheric pressure to 0.79 at 50,000 (by extrapolation). The present results were corrected by a factor varying linearly over the entire range from 0.69 at atmospheric to 0.93 at 100,000. The results are normal in every way, smooth decrease with upward curvature.

Tantalum. This was from the same laboratory stock from the same source as the columbium. It was used in the original sheet thickness of 0.003 inch and in a width of 0.035 inch. Four runs were made with two grades of carboloy. The proportional change of resistance at 100,000, in terms of the resistance at 30,000 as fiducial, varied from 0.087 to 0.114. The average was used. Compared with previous measurements [53] to 30,000 the present results give too large a decrease of resistance. The ratio increases with pressure, but the ratio is not as smooth as usual and the final results are in more doubt. Final correction was made by using a correction factor increasing linearly with pressure from 0.55 at atmospheric pressure to 0.77 at 100,000. The final results are shown in Table XII.

The behavior is normal in every way.

Arsenic. The material was old highly purified single crystal stock. It is brittle and fragile and difficult to handle. The specimens were prepared in two radically different ways. The first method was by splitting off from the cleavage plane of a single crystal with a razor blade a thin slab, reducing this in thickness to about 0.005 inch by squeezing cold between carboloy platens, and then worrying out of the flake thus formed a very roughly shaped specimen. This latter was difficult because of the many cracks produced by the flattening process and the extreme fragility of what hung together. Finally, however, two specimens were produced which appeared to be sound. Runs with these two specimens gave results entirely different qualitatively. The first gave a smooth decrease with normal upward curvature to about 70,000, where there was a slight inflection followed by decrease to 100,000 with increasing downward curvature. The second gave a decrease to a minimum at 40,000, rise to a maximum at 80,000, and drop with abnormal downward curvature to 100,000. Previous measurements [54] to 12,000, the previous maximum,

had prepared me for unusual and nonreproducible effects with this material, but not for variation as great as this. Accordingly, other specimens were prepared by hot extrusion from a steel die. As far as I know this material has not been extruded before. The temperature of the extrusion is apparently rather critical; if temperature is too low arsenic will not extrude at all and if too high will completely vaporize away as it emerges from the die. The method used was empirical, heating the die with a gas torch while pressure was exerted on the extruding piston and taking the wire when it came. Enough wire 0.0055 inch in diameter was secured in this way to allow three different set-ups, but not more than enough, the wire completely vaporizing away at the last. The specimens were prepared by laying five lengths of the wire side by side in a trough preformed in the AgCl. The depth of the trough was slightly less than the diameter of the wire, so that when the sandwich was subjected to its final consolidation the AgCl flowed around the wire. In spite of the extreme brittleness of this material examination under the microscope disclosed no initial fractures, and the behavior of electrical resistance bore this out. Three runs were made with the extruded wire, with two grades of carboloy. The three runs were in qualitative agreement and agreed with one of the runs with the specimens prepared by the other method, namely decrease to a minimum, rise to a maximum, and drop. It is to be presumed that the orientation in the extruded wire is more or less haphazard, so that the three runs with minimum and maximum may be assumed to be a sort of average for different directions in the crystal. The similar behavior of the specimen prepared by squeezing from the cleavage flake may be ascribed to the disorientation produced by the process of squeezing. But since one specimen from the cleavage flake showed a radically different behavior, the presumption is that there is one direction in the crystal with that sort of behavior and qualitatively different from the mean.

There seems no basis for comparison with previous results, which exhibited various non-reproducible breaks in direction and two-fold variation in numerical magnitudes. The rough general average of previous results to 12,000 was a decreasing resistance with abnormal downward curvature. The best that it seems possible to do with present results is to average the four qualitatively similar minimum-maximum results, and to reproduce for itself without correction the one qualitatively different. The proportional decrease of resistance at 100,000 of the resistance at atmospheric pressure as fiducial of the four minimum-maximum runs varied from 0.052 to 0.089, average 0.072. This is much less than for the other specimen, with a corresponding decrease of resistance of 0.302. The numerical results are given in Table XIII and Figure 11.

Antimony. The material was old single crystal stock, and presumably of high purity, having been prepared from Kahlbaum "K" material. It is very brittle and requires special manipulation. One run was made on a sliver of suitable dimensions obtained by cleaving off flakes with a razor blade from the cleavage face of a massive crystal. However, the production of this specimen proved to be a matter of good luck, and I was not able to make another in spite of destroying much single crystal material. Accordingly, the method used with arsenic was adopted, namely cleaving off as thin a flake as possible, squeezing this to the required thickness,

TABLE XIII

	R/R$_0$			
	Arsenic			
Pressure kg/cm^2	Haphazard orientation	Mostly in cleavage plane	Antimony	Bismuth
0	1.000	1.000	1.000	1.000
10,000	.959	.933	1.060	
20,000	.925	.882	1.104	(a)
				(b)
30,000	.901	.844	1.103	.604
40,000	.891	.814	1.078	.567
50,000	.894	.789	1.021	.546
60,000	.907	.767	.938	.528
70,000	.925	.750	.837	.517
80,000	.937	.734	.756	.498
90,000	.938	.718	.674	.485
100,000	.928	.698	.605	.474

[a] Transition I–II at 25,650. Resistances 1.514 and .239
[b] Transition II–III at 27,080. Resistances .236 and .617

here about 0.006 inch, between carboloy platens, and then worrying out of this flake a roughly shaped specimen. Runs made on two specimens fashioned in this way agree qualitatively with the results on the single crystal flake, namely rise to a maximum followed by drop and reversal of curvature to normal in the upper 20,000 kg/cm^2. This eventual reversal of curvature is of course inevitable, for otherwise resistance would become negative at sufficiently high pressure.

The three specimens thus measured may be presumed, because of the method of preparation, to have a strongly preponderating orientation of the basal plane in the length. Previous measurements[55] to 30,000 had shown strong orientation effects. Thus when the axis is at 87° to the length (cleavage plane 3° to the length) resistance increases by about 5 per cent to a maximum in the neighborhood of 10,000, and from here decreases with abnormal downward curvature to 0.95 at 30,000. When

the axis is at 41° to the length, however, resistance increases with abnormal downward curvature over the entire 30,000 with an extrapolated maximum at 31,250. It was to be expected therefore that with a greater preponderance of lower orientations the maximum would be accentuated. A run was accordingly made on a specimen prepared by grinding to suitable thickness a wire prepared by hot extrusion from commercial material some 30 years ago. The results were not as expected at all, but from the start resistance decreased, at first slowly, then more rapidly, and

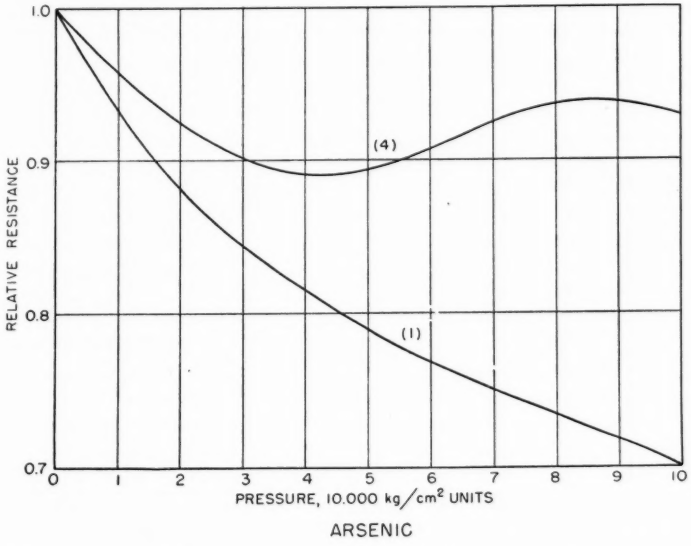

FIGURE 11. The relative resistance to 100,000 kg/cm^2 of arsenic. Curve (4) is the average of four similar specimens and curve (1) the curve for a single exceptional specimen.

finally with reversal of curvature. The only explanation of this seemed to be inferior chemical purity in the commercial material. Accordingly wire was freshly prepared by hot extrusion from the high purity single crystal stock. Extrusion was more difficult than with the commercial material and only short lengths of suitably smooth wire of 0.0045 inch diameter was obtained (most of it was curled). This was mounted like arsenic in three parallel lengths and a run made to 100,000. The result was now as expected, an enhanced maximum as compared with the three

others, and a displacement of the pressure of the maximum toward higher pressures.

In view of the strong orientation effects no good way of adjusting these values to agreement with the former ones at 30,000 presents itself, and the four runs were simply averaged. It would seem that this average corresponds to an angle between the axis and the length of between 70° and 80°. The results are shown in Table XIII and Figure 12. From a study of the variation in the pressure of the maximum it would seem

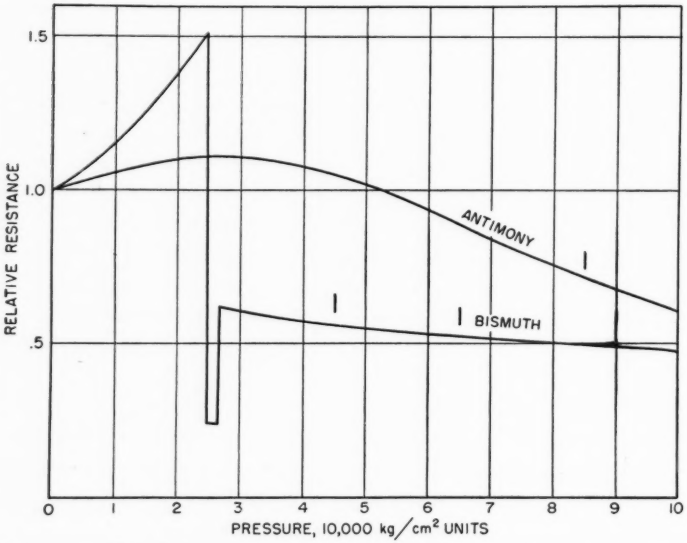

FIGURE 12. The relative resistances to 100,000 kg/cm² of antimony and bismuth. The vertical dashes show the location of polymorphic transitions as disclosed by the measurements of volume.

probable that if any adjustment were made of the tabulated results it should be in the usual direction of a stretching out of the changes of resistance so that both increases and decreases would become larger. However, the best way of doing this did not appear.

None of the specimens showed any trace of the polymorphic transition found previously at 85,000 on measurement of compressibility.

Bismuth. The material was from my highly purified electrolytic stock, cast into single crystal form after electrolytic deposition. Specimens were

prepared by several methods. Two specimens were cut from a sheet 0.002 inch thick made by allowing a drop of molten metal to solidify between carboloy platens clamped to within 0.002 inch of contact by suitable shims. Two specimens were cut from a thin film made by allowing a molten drop to fall from a suitable height onto a cold iron plate, spattering itself out into a thin film, which was further squeezed cold between carboloy platens to 0.002 inch thick. In order to accentuate any possible orientation effects a fifth specimen was made by cleavage with a sharp knife from the basal plane of a single crystal. Bismuth in thin section is fairly flexible and none of the mechanical difficulties were found that had made manipulation of arsenic and antimony so difficult.

Bismuth is known to have five polymorphic transitions [56] up ot 100,000 (six polymorphic forms), including two with large volume change near 25,000. On passing through these transitions and back the original orientation is not recovered, but the original single crystal is converted into a multi-crystal. Orientation effects would therefore not be expected in the present work, and none were found. In fact, the structure of the high pressure modifications is not known; if it should happen to be cubic then no orientation effects can occur in principle under any conditions with these modifications. The first transition, I—II, is known from previous work [57] to be accompanied by a drop of resistance by the large factor 6.34. The precise value of this factor is not of definite significance because of the unknown orientation effects. The second transition, II—III, is known from previous work to be accompanied by a rise of resistance by a factor 2.62, the rise being against the direction of volume change and therefore abnormal. In the present measurements these figures were qualitatively confirmed; the resistance drops at the I—II transition by an amount varying in the five runs from 2.5 to 4.1, and in four out of the five runs rises at the II—III transition by a factor varying from 1.25 to 1.79. The fifth run gave a factor 0.8 (drop).

The presence of two large transitions near 25,000 nullifies any attempt to find a satisfactory basis for reducing the present measurements to agreement with the former ones below 30,000. However, the evidence is that the agreement is unusually close in the range below the I—II transition, the present increase of proportional resistance between atmospheric pressure and 25,090 varying from 1.39 to 1.50 against a former value of 1.52. Accordingly the present values were averaged, without further correction, in the range 40,000 to 100,000, choosing the fiducial resistance at 40,000 so as to agree with the former value extrapolated from 30,000 to 40,000. In the range above 40,000 the five runs were in rather better agreement than usual, the extreme values for proportional change of resistance at 100,000, in terms of that at 40,000 as fiducial,

being 0.160 and 0.170. All five runs in the range above 40,000 agreed in giving almost no perceptible effect of the other three known transitions. Any individual run showed irregularities which by the exercise of imagination could be correlated with the known transitions, but the pressures at which the irregularities occurred showed no consistent pattern, and even the sign of the irregularities was not always consistent. The final results, which are given in Table XIII and Figure 11, have therefore been obtained by smoothing over any possible transition effects.

The failure of the known high pressure transitions to manifest themselves by changes of resistance is doubtless connected with the smallness of the volume changes. For convenience of reference the pressures and volume changes of the several transitions at 25° are listed.

Transition	Pressure kg/cm²	$\Delta V/V_0$
I–II	25,650	0.0460
II–III	27,080	0.0295
III–IV	45,000	0.006
IV–V	65,000	0.005
V–VI	90,000	0.012

The volume changes at the high pressure transitions are thus small compared with the two at lower pressures, but if the discontinuity of resistance is proportional to the volume change they should nevertheless have been far beyond the errors of measurement. It would appear that the high pressure transitions are accompanied by a much less drastic change in the mechanism of conduction than the low pressure transitions.

Chromium. This was electrolytic material prepared at the Bureau of Standards, the identical material that was used in recently published[58] measurements of resistance to 30,000. For the present measurements pieces were ground to dimensions from the electrolytically deposited tube. There were brittle places in the tube as deposited. These were eliminated as far as possible by first cutting long strips from the tube and breaking these in the fingers into as short pieces as would break with the exercise of considerable force. The dimensions of the final specimens varied in thickness from 0.0027 to 0.0035 inch, and in width from 0.030 to 0.037 inch.

Four runs were made with two grades of carboloy. The changes of resistance at 100,000, in terms of the resistance at 30,000 as fiducial, varied from 0.128 to 0.141. In spite of this fair agreement, there was much more doubt than usual as to the best way of reducing these results so as to agree with the former ones to 30,000. Some of this doubt may be intrinsic in the material. Previous measurements had shown a sharp cusp at about 4,000 kg/cm² in the resistance-pressure relation, and further-

more the resistance at this cusp did not agree with previous low pressure anomalies exhibited by another specimen of presumably high purity in measurements to 12,000. Two methods of reduction were employed. In the one, the ratio of former resistance changes to the present were plotted as a function of pressure. This ratio increases roughly linearly with pressure to 50,000 (by extrapolation of former results). The results were corrected by using a factor running linearly from 1.00 at atmospheric pressure to 2.40 at 100,000. The second method of correction was to multiply the present changes of resistance by that constant factor which

TABLE XIV

Pressure kg/cm^2	R/R$_0$			
	Chromium	Molybdenum	Tungsten	Uranium
0	1.000	1.000	1.000	1.000
10,000	.827a	.987	.987	.947
20,000	.774	.975	.975	.904
30,000	.731	.963	.963	.866
40,000	.701	.951	.951	.837
50,000	.673	.940	.940	.812
60,000	.647	.929	.930	.790
70,000	.624	.919	.920	.770
80,000	.601	.909	.911	.752
90,000	.580	.900	.903	.737
100,000	.558	.892	.895	.724

[a] Cusp at 4,000; see text.

would reduce the present results to agreement with the former results at 10,000 and 30,000. These two methods of correction usually give closely concordant results, but here the first method gave for the resistance at 100,000 in terms of resistance at atmospheric pressure as unity the value 0.493, whereas the second method gave 0.623. In the absence of other compelling considerations the two methods were averaged to give the final values in Table XIV. The uncertainty in the final values ultimately stems from irregularity in the low pressure behavior.

Molybdenum. The material was sheet 0.0015 inch thick from the stock of the Raytheon Manufacturing Company. It was annealed in vacuum in quartz at a white heat. Four runs were made with two grades of carboloy with two widths, 0.010 and 0.020 inch. The proportional changes of resistance at 100,000 in terms of the resistance at 30,000 as unity, varied from 0.076 to 0.098. The average was used. Compared with previous measurements [59] to 30,000 the present decrements of proportional resistance are too large. Agreement becomes better toward the higher pressures.

The ratio varies approximately linearly with pressure. The final results were obtained by using a correction factor increasing linearly with pressure from 0.54 at atmospheric pressure to 0.89 at 100,000. The results are given in Table XIV; there is no particular feature.

Tungsten. This material was 0.001 inch ribbon which I owe to the courtesy of Dr. C. G. Smith of the Raytheon Manufacturing Company. It was used without annealing and in a single width 0.035 inch. Four runs were made with two grades of carboloy. The decrement of proportional resistance at 100,000, in terms of resistance at 30,000 as unity, varied from 0.089 to 0.097. Compared with previous measurements [60] to 30,000 the present decrements are too large, the agreement becoming better at higher pressures. The ratio of the decrements increases linearly with pressure. A final correction factor was used increasing linearly from 0.42 at atmospheric pressure to 0.75 at 100,000. The final results are shown in Table XIV; they are without special feature.

Uranium. This was the same material as previously used in measurements of compression [61] to 100,000. To form the specimens a sliver was cut from the massive ¼ inch block with a knife, squeezed cold between carboloy platens to a thickness of 0.003 to 0.004 inch, and cut to widths of 0.03 to 0.04 inch. Four runs were made with two grades of carboloy. The high pressure results were fairly consistent. The proportional changes of resistance at 100,000, in terms of resistance at 30,000 as unity, were: 0.147, 0.171, 0.189, and 0.150. The low pressure results were not so consistent, however, the proportional change of resistance in the first 20,000 kg/cm^2 varying from 0.10 to 0.20. Some of this variation is perhaps to be associated with the non-cubic symmetry of the lattice.

There are no adequate previous results for comparison. The only previous measurements [62] are to 12,000 on a specimen of presumably much inferior purity. This specimen showed a linear drop of resistance with pressure with coefficient -4.36×10^{-6}, which at 20,000 would give a decrement of 0.087 against 0.10 to 0.20 above. I attempted without success to form wire suitable for new measurements to 30,000 by the same method of hot extrusion employed for neodymium and the other rare earths. The steel die reached its softening point before the uranium. Under the circumstances it seems that the best course is to give merely the average of the four runs without attempt at correction. The zero is extrapolated; the greatest doubt is at low pressure. These results are given in Table XIV. It will be seen that there is no feature in the results, and in particular no indication of any transition below 100,000.

Selenium. This was highly purified material which I owe to the kindness of Professor von Hippel of M.I.T. It was supplied to me in several

forms of different heat treatments, but only one of these forms was used for the present measurements. This was in slender single crystal needles with a high metallic luster of the order of 2 cm long. An amorphous form prepared by heating to 200° C for two days had an initial resistance 10 times higher than the crystalline needles. Two runs were made on the crystal. For one of these a thin single crystal was squeezed between carboloy platens to about half thickness at 0.003 inch, and from this squeezed plate a roughly shaped specimen was picked out with a needle. For the other specimen a single crystal was fortunately found thin enough (0.0037 inch) to permit use without further thinning, and the specimen was trimmed out of this with a razor blade. The length of each specimen was along the original length of the crystal needle. The initial specific resistance at room temperature of the crushed needle was 4.2×10^3 and of the other specimen 3.64×10^3 ohm cm. The resistance of the specimens as mounted is initially very high, of the order of a megohm, so that a special arrangement of the circuits was necessary. Under 100,000 kg/cm^2 resistance decreases by something of the order of 10,000 fold, so that resistance has to be plotted on a logarithmic scale. The qualitative nature of the results was the same for both specimens. Plotted on a logarithmic scale, the curve drops with slight upward curvature to about 56,000 kg/cm^2. Here there is an obtuse upward knee, beyond which the curve drops linearly to 100,000. At the knee both runs showed a slight downward jump of resistance amounting to a drop of about 25 per cent. It would seem highly probable that the jump means a polymorphic transition, but if so a transition to another non-metallic form.

Previous measurements[63] on the volume to 100,000 on material originally in the glassy state had shown irregularities which were interpreted as due to some sort of permanent change. However, there is probably no correlation with the present results on crystalline material.

On a logarithmic basis the two runs were in fair quantitative agreement, for the one run $\log_{10} R_0/R_{100,000}$ having the value 3.95 and for the other 4.15. The two logarithms were averaged and the final results are shown in Table XV. There are no previous measurements to which these high pressure results can be corrected.

Tellurium. This material is of special interest because under normal conditions it is a semi-conductor which under pressure is pushed toward the metallic condition. Previous measurements[64] to 30,000 had given a decrease of resistance by a factor varying from 400 to 600 fold depending on the orientation of the single crystal. Furthermore, at 30,000 the temperature coefficient of resistance has become positive, like a metal.

Six different runs were made to 100,000 on three grades of material. Tellurium is excessively brittle. Five of the six runs were handled by the extruded wire technique, laying five or six lengths of wire 0.005 to 0.006 inch in diameter side by side in a trough pressed in the AgCl sandwich. The sixth run was on a thin sliver cleaved out of a single crystal, with length along the trigonal axis. The material of the sliver was old Kahlbaum stock. Three of the runs were made on the same old extruded stock on which previous measurements were made. This was made from as pure initial material as was then available and was purified

TABLE XV

RESISTANCE OF SELENIUM

Pressure kg/cm²	$\log_{10} R/R_0$
0	0.00
20,000	− 1.26
40,000	− 2.22
56,000	− 2.85
	− 2.95a
60,000	− 3.05
80,000	− 3.55
100,000	− 4.05

[a] Transition.

further by crystallization, but I have no explicit data as to purity. Measurements on these four specimens differed greatly from the former measurements to 30,000, the drop of resistance between atmospheric pressure and 30,000 now being by a factor of only 5 against the 400 to 600 formerly. Accordingly the measurements were repeated with some highly purified tellurium made by distillation in helium which I owe to the kindness of Professor Harry Hall, by whom it had been prepared at Durham, N. H. Professor Hall found that $\log_{10}$ of the resistance of this material is linear in 1/T in the range −40° to 350°C, and the specific resistance satisfies the formula: $\rho = A \exp E_\varepsilon/2\kappa T$, where $A = 8.90 \times 10^{-4}$ ohm cm, and $E_\varepsilon = 0.323$ ev. It was formed into wire of 0.005 inch diameter by hot extrusion and two runs made with it. Resistance was now found to drop by a larger factor in the first 30,000 kg/cm² than for the other specimens, namely by factors of 16.1 and 19.3, but still is far short of the previous factors 400 and 600. So large a discrepancy cannot possibly be caused by any geometrical distortion associated with non-hydrostatic stress, and the only conclusion would seem to be that the effects of internal strain are unusually large for this material. In

view of this it hardly seems worth while to reproduce the numerical results in any detail, and certainly not worth while to attempt to devise a method of correction that will secure agreement with the previous results.

Tellurium is known to have a polymorphic transition [65] with a 5.5 per cent volume discontinuity at 45,000. It is a natural surmise that the high pressure modification will be a metallic conductor. All of the present runs gave a large drop of resistance at a pressure never lower than 45,000 and never higher than 59,000. The lower pressures are more significant here because of the possibility of superpressing, and these results may be regarded as giving essential confirmation of the correctness of the present pressure scale. The factor by which the resistance dropped at the transition varied from 13.8 for the single crystal sliver to 26.7 for one of the highly purified specimens, average 20.1. So large a drop substantially confirms the hypothesis that the high pressure modification is metallic, as does also the absolute value of the specific resistance, which is approximately 13×10^{-6} ohm cm immediately above the transition. Above the transition all runs agreed in a smooth drop of resistance to 100,000. Logarithm of resistance is linear in pressure in this range. The variation between the different runs in this range was 6 per cent on both sides of the mean. In the range above the transition the mean rate of resistance drop is at the rate of 8.3 per cent for 10,000 kg/cm^2 pressure increase.

Manganese. Pure manganese has not, as far as I know, been produced in wire form. The particular difficulty is the polymorphic transition with volume change so large that the massive metal spontaneously fractures on cooling. Recently the Bureau of Mines investigated the possibility of various industrial uses for high grade manganese, and produced manganese of approximately 97 per cent purity in rod and wire form. I obtained some of this through the courtesy of Dr. Bruce Rogers. The composition was stated to be: Ni 1.02, Cu 2.33, S 0.1, balance thought to be practically all manganese, but not analyzed further. Because of the lesser interest in this material because of its inferior purity only two runs were made to 100,000 with two grades of carboloy. The specimens were prepared by grinding to a thickness of 0.0025 inch and width 0.037 inch from a wire 0.0625 inch in diameter.

The change of proportional resistance at 100,000 in terms of the resistance at 30,000 as fiducial, was 0.145 and 0.142. Both runs agreed in showing unusual curvature. Up to about 50,000 resistance decreases with normal upward curvature, but here there is a point of inflection followed by downward curvature with probably a second reversal and normal curvature again above 95,000.

The measurements to 30,000 went smoothly, with no perceptible hystere-

sis. The results, in terms of the usual $-\frac{1}{p}\frac{\Delta R}{R_0}$, are shown in Table XVI. The average temperature coefficient of resistance at atmospheric pressure between 0° and 25° was 0.00325. This is appreciably lower than the expected 1/T (0.00366); the difference is to be ascribed to the impurity. The specific resistance at atmospheric pressure and 0° was 6.36×10^{-5}.

The measurements to 100,000, reckoned from the resistance at 20,000 as fiducial, gave a smaller change of resistance below 20,000 and a

TABLE XVI

RESISTANCE OF MANGANESE TO 30,000 KG/CM²

Pressure kg/cm²	$-\frac{1}{p}\frac{\Delta R}{R_0}$
0	4.22×10^{-6}
5,000	3.85
10,000	3.54
15,000	3.27
20,000	3.04
25,000	2.83
30,000	2.63

larger change above than the 30,000 measurements, the ratio varying smoothly from 1.114 at atmospheric pressure to 0.932 at 30,000. This correction factor was extrapolated by smooth graphical construction to the value 0.73 at 100,000, and the results so corrected are given in Table XVII. There is obviously room for considerable doubt in the absolute values at the top pressure. Qualitatively, the results are somewhat unusual in the double reversal of curvature already mentioned.

Iron. The material was "decarburized steel" which I owe to the courtesy of Dr. R. F. Mehl of the Carnegie Institute of Technology. It had been prepared by treating in wet hydrogen at 1200°C for one month. The original steel had the analysis: C 0.067, Mn 0.38, P. 0.014, S 0.024, Si 0.12. After treatment carbon was undetectable microscopically (less than 0.005 per cent), sulfur was probably less than 0.005 per cent, and hydrogen less than 0.0005 per cent. It was prepared for the present measurements by rolling from 0.04 inch to 0.002 or 0.001 inch thickness, with an annealing after rolling to red heat in quartz in vacuum, and was used in two widths, 0.020 and 0.010 inch. Six runs were made, of which two had to be discarded because of cracking of the carboloy platens. The four good runs were all made with the same grade of carboloy, #883.

The agreement of the four runs was good; the change of proportional resistance at 100,000, in terms of resistance at 30,000 as fiducial, varied from 0.100 to 0.105. Compared with previous measurements [66] to 30,000 the present decrements of resistance were too large, the reduction factor varying linearly with pressure from 0.80 at atmospheric pressure to 0.90 at 50,000 (extrapolated). The final results were obtained by using a correction factor varying linearly to unity at 100,000. The final results are given in Table XVIII. The proportional resistance at 100,000, in terms of resistance at atmospheric pressure as unity, given in the table is 0.841.

TABLE XVII

RESISTANCE OF MANGANESE TO 100,000 KG/CM^2

Pressure kg/cm^2	R/R_0
0	1.000
10,000	.965
20,000	.939
30,000	.921
40,000	.909
50,000	.900
60,000	.892
70,000	.883
80,000	.872
90,000	.856
100,000	.841

This is to be compared with the value 0.828 which would have been obtained if no correction procedure had been applied. The behavior of resistance is normal in every way, smooth drop with upward curvature.

Nickel. The material was cut from a single crystal which I owe to the courtesy of Dr. R. M. Bozorth of the Bell Telephone Laboratories. It is the same material as was used in recent measurements of compressibility [67] to 30,000. The purity is thought to be high, with no element present to as much as 0.01 per cent. A piece from the single crystal was rolled to 0.002 inch thickness, annealed to red heat in vacuum, and cut to widths of 0.010 and 0.020 inch for the measurements. Four runs were made with two grades of carboloy. The proportional change of resistance at 100,000, in terms of resistance at 30,000 as unity, varied from 0.099 to 0.111. The average was used. Compared with previous measurements [68] to 30,000 the present decrements of resistance are too large. The ratio increases roughly linearly with pressure; for the final results a correction factor was used increasing linearly from 0.78 at atmospheric pressure to 0.91 at

100,000. Former measurements showed a kink in the resistance curve at 10,000. This is on too small a scale to attempt to reproduce here, and the final results in Table XVIII are smoothed right through this point. Except for this small kink at 10,000 the resistance behaves conventionally.

Cobalt. This, like the nickel, was single crystal stock from Dr. Bozorth of the Bell Telephone Laboratories. It was "Katanga" cobalt, and a typical analysis showed 0.05 per cent iron and 0.01 per cent copper as the principal impurities. The specimens for the present measurements were prepared by cutting a thin disc from across the end of the single crystal,

TABLE XVIII

Pressure kg/cm²	R/R_0		
	Iron	Nickel	Cobalt
0	1.000	1.000	1.000
10,000	.977	.982	.991
20,000	.956	.965	.983
30,000	.936	.948	.976
40,000	.919	.933	.970
50,000	.903	.918	.965
60,000	.888	.904	.961
70,000	.875	.892	.958
80,000	.862	.880	.955
90,000	.851	.869	.953
100,000	.841	.858	.951

that is, with the principal axis perpendicular to the plane of the disc, swaging the disc down to a thickness of 0.006 inch by hot hammering, filing further to a thickness of 0.002 inch, annealing to red heat in vacuum, and cutting to widths of 0.022 and 0.047 inch for the measurements. Four runs were made with two grades of carboloy. The proportional change of resistance at 100,000, in terms of resistance at 30,000 as unity, varied from 0.041 to 0.047. The effect is therefore unusually small. The average of the four runs was used. Compared with previous measurements[60] to 30,000 the decrements of resistance were too large by a factor of nearly 2. This is not surprising in view of the absolute smallness of the effect. The correction factor showed a slight trend with pressure, and the final results, which are shown in Table XVIII were obtained with a correction factor increasing linearly with pressure from 0.55 at atmospheric pressure to 0.58 at 100,000. Cobalt was previously found to have certain irregularities at the low pressures, but these are on too small a scale to attempt to reproduce here. In addition to the smallness of the effect, cobalt is unusual in the flattening out of the curve, suggesting a minimum not far beyond

100,000. Any conclusion with regard to such a minimum must, however, be used with considerable caution.

Rhodium. This material was originally obtained in 1923 from Johnson and Mathey, London, in the form of a bar swaged to dimensions at red heat. For the present measurements a piece was cut from the former compressibility specimen [70] and further hammered at a red heat to a thickness of 0.002 to 0.003 inch. Specimens were cut to widths of 0.030 to 0.040 inch, and four runs were made with two grades of carboloy. The proportional change of resistance at 100,000, in terms of resistance at 30,000 as unity, varied from 0.082 to 0.091; the average was used. Compared with

TABLE XIX

Pressure kg/cm^2	R/R_0			
	Rhodium	Palladium	Iridium	Platinum
0	1.000	1.000	1.000	1.000
10,000	.984	.980	.986	.981
20,000	.968	.960	.973	.963
30,000	.953	.942	.960	.947
40,000	.939	.925	.948	.931
50,000	.925	.909	.936	.916
60,000	.912	.894	.924	.903
70,000	.900	.881	.914	.891
80,000	.889	.869	.904	.880
90,000	.880	.858	.895	.870
100,000	.872	.847	.886	.861

previous measurements [71] to 30,000 the decrements are too large, the ratio showing a non-linear increase with pressure. The final results are given in Table XIX; they were obtained by using a correction factor varying from 0.656 at atmospheric pressure, to 0.888 at 50,000 to 1.000 at 100,000. Resistance drops smoothly with increasing pressure, and the behavior is entirely normal.

Palladium. This material was originally obtained from Baker and Company in the form of wire 0.007 inch in diameter, and had been formerly [72] used in measurements of the effect of pressure on resistance at low temperatures. For the present measurements the wire was rolled flat to a thickness of 0.002 inch and degassed by heating to 900°C in vacuum. Four runs were made with two grades of carboloy. The proportional change of resistance at 100,000, in terms of the resistance at 30,000 as unity, varied from 0.098 to 0.102; the average was used. Compared with previous measurements of resistance [73] to 30,000 the decrements of resistance are too large, the agreement becoming better at higher pressures. The final results, shown

in Table XIX, were obtained with a correction factor varying linearly with pressure from 0.81 at atmospheric pressure to 1.00 at 100,000. Resistance decreases normally with pressure.

Iridium. This was "pure" material from Baker and Company in the form of sheet 0.0016 to 0.0019 inch thick. Four runs were made with two grades of carboloy, the specimens varying in width from 0.020 to 0.037 inch. The proportional change of resistance to 100,000, in terms of resistance at 30,000 as unity, varied from 0.073 to 0.084. Compared with previous measurements [74] to 30,000 the decrements of resistance are too large, the agreement becoming better at the higher pressures. The final results were obtained by using a correction factor varying linearly with pressure from 0.586 at atmospheric pressure to 0.88 at 50,000, above which the factor

TABLE XX

RESISTANCE OF Ag_5Cd_8 TO 30,000

Pressure kg/cm²	R/R_0
0	1.0000
5,000	.9858
10,000	.9737
15,000	.9630
20,000	.9532
25,000	.9440
30,000	.9354

Average temp. coef. 0°–25°C, .00237
Specific resis. at 0° at 0 kg/cm², 1.22×10^{-5} ohm cm

was carried by smooth graphical extrapolation to 1.000 at 100,000. The results are shown in Table XIX; resistance decreases smoothly and normally.

Platinum. The material was "iridium free" sheet stock 0.0015 inch thick from Baker and Company. After cutting to dimensions the specimens were annealed at white heat. Four runs were made with two grades of carboloy on widths varying from 0.010 to 0.020 inch. The proportional change of resistance at 100,000, in terms of resistance at 30,000 as unity, varied from 0.099 to 0.112; the average was used. Compared with previous measurements [74] to 30,000, the decrements of resistance are too large, the agreement becoming somewhat better at the higher pressures. The final results were obtained with a correction factor increasing linearly with pressure from 0.77 at atmospheric pressure to 0.86 at 100,000. The extrapolation of this factor beyond 30,000 cannot be regarded as very secure, but the details are of no great importance because of the narrow range of

variation and the closeness of the factor to unity. Final results are shown in Table XIX; resistance decreases with pressure with normal upward curvature.

Intermetallic Compounds. Measurements were made on nine intermetallic compounds of comparatively simple structure. The resistance of seven of these has been previously measured [75] to 30,000, and that of one of the others, Ag_5Cd_8, is here measured to 30,000 and published in Table XX for the first time. The ninth, Cu_5Cd_8, has previously been measured [76] only to 12,000. Measurements on these nine compounds were much less complete than on the pure metals. Only one set-up was used with each, and the

TABLE XXI

Pressure kg/cm^2	R/R$_o$								
	CuZn	AgZn	AuZn	Cu_5Zn_8	Ag_5Zn_8	Cu_5Cd_8	Ag_5Cd_8	Ag_2Al	Sb_2Tl_7
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
10,000	.980	.963	.967	.969[a]	.996	.908	.974	1.001	.917
20,000	.961	.932	.938	.951	.994	.836	.953	1.003	.852
30,000	.944	.906	.912	.936	.994	.777	.935	1.005	.798
40,000	.928	.883	.889	.922	.995	.729	.921	1.008	.752
50,000	.915	.861	.869	.911	.999	.694	.910	1.011	.712
60,000	.903	.840	.851	.902	1.004	.664	.901	1.015	.676
70,000	.892	.819	.835	.894	1.012	.639	.894	1.019	.645
80,000	.883	.797	.822	.888	1.022	.619	.889	1.023	.616
90,000	.875	.775	.809	.883	1.034	.600	.885	1.029	.591
100,000	.868	.755	.799	.879	1.050	.585	.884	1.035	.568

[a] Cusp at 5,000.

precise results are accordingly in more doubt. The measurements were undertaken primarily in the spirit of finding whether there were any new transitions of the first or second kind or other unusual features at high pressures, as perhaps might have been anticipated from the nature of the material. The results obtained should be competent to give information on these points. No such features were in fact found. The only noteworthy qualitative feature was a minimum in the resistance of Ag_5Zn_8; the minimum is so flat and the absolute magnitude of the pressure effect so small that the quantitative relations at this minimum as tabulated must be taken with great caution. The present uncorrected measurements to 100.000 gave a minimum at 70,000, whereas the former measurements to 30,000 located a minimum at about 27,000. The correction factor was determined so as to preserve the latter location of the minimum.

In view of the less precise nature of the results on these intermetallic compounds, only the final results are presented in Table XXI without giving

the details of the correction procedures for the different compounds, some of which must be recognized to have considerable uncertainty.

Iron-Nickel Alloys. Since I had on hand a fairly extensive material, seven compositions in all, an investigation was made in the same spirit as that on the intermetallic compounds, to discover whether there are any new qualitative features at high pressures. Five of the compositions were in the form of wire which I owe to the kindness of Professor McKeehan of Yale, and for which I have published measurements [77] of the effect of pressure on resistance up to 12,000. The wire was 0.010 inch in diameter. It was prepared for these measurements by annealing to a red heat, squeezing flat to a thickness of approximately 0.002 inch between carboloy platens, annealing

TABLE XXII

RELATIVE RESISTANCE OF IRON-NICKEL ALLOYS

Pressure kg/cm²	Fe 90, Ni 10	Fe 80, Ni 20	Fe 75, Ni 25	Fe 70, Ni 30	Fe 62.5, Ni 37.5 Invar	Fe 60, Ni 40	Fe 30, Ni 70 Permalloy
0	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
10,000	.9997	.9609	1.0273	1.0866	1.0243	1.0849	1.0045
20,000	.9945	.9547	1.0640	1.1998	1.0327	1.1592	1.0082
30,000	.9858	.9550	1.0987	1.3166	1.0269	1.2154	1.0107
40,000	.9781	.9566	1.1272	1.4381	1.0128	1.2540	1.0132
50,000	.9716	.9587	1.1513	1.5160	.9953	1.2771	1.0169
60,000	.9661	.9598	1.1746	1.5986	.9784	1.2854	1.0205
70,000	.9614	.9618	1.1934	1.6690	.9640	1.2858	1.0265
80,000	.9575	.9642	1.2116	1.7310	.9523	1.2819	1.0330
90,000	.9540	.9664	1.2287	1.7820	.9480	1.2747	1.0408
100,000	.9510	.9680	1.2514	1.8262	.9293	1.2650	1.0482

again to a red heat and trimming to a width of 0.020 inch. The other two compositions were: (1) "permalloy," Fe 30, Ni 70, which I owe to the courtesy of Dr. Bozorth, and (2) "invar," of nominal composition Fe 62.5, Ni 37.5, from the stock of the laboratory machine shop.

Only one run was made on each composition. In the five cases where previous measurements had been made to 12,000 the present results were corrected to give agreement over the common range. The correction was usually made in the simplest possible way with a factor constant over the entire range to 100,000. There are no previous measurements on permalloy or invar, and the present results are here given without correction.

The results are listed in Table XXII. Figure 13 gives a general survey of the results. In the top part of the figure the results for the different alloys are shown qualitatively, *not* to scale, and with exaggeration of the curvatures; in the bottom part of the figure the results are all given together on

the same scale. It will be seen that unlike the intermetallic compounds there is here a wealth of new feature at high pressure, commonly taking the form of unusual reversals of curvature. It suggests itself that alloys offer a fertile field for future study.

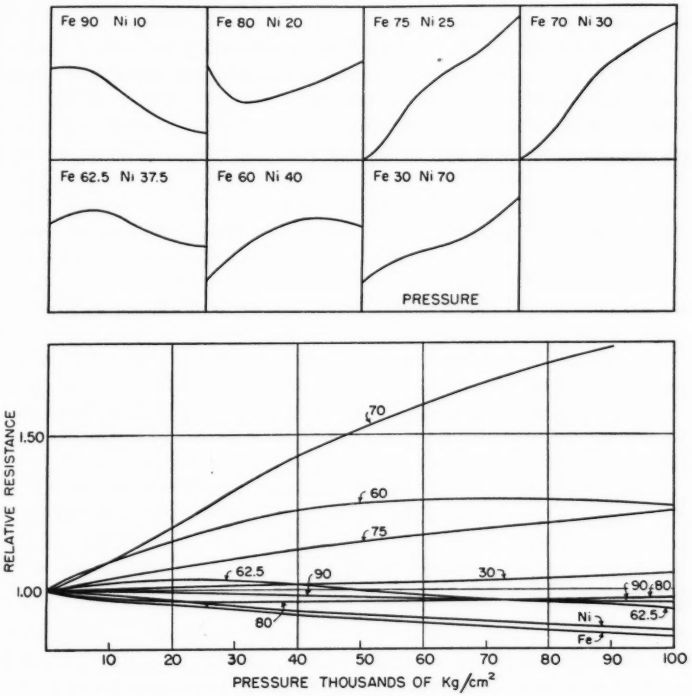

FIGURE 13. The resistance to 100,000 kg/cm^2 of a series of iron-nickel alloys. In the upper part of the diagram the curves are exaggerated so as to bring out the qualitative features; in the bottom part of the diagram the relative resistances of the various alloys are shown to scale.

In my notes I found a determination of the compressibility of invar at 30° to 12,000 which apparently has not yet been published. I take the occasion to give it here. Using all corrections for the most recent values for iron the formula is:

$$-\Delta V/V_0 = 9.96 \times 10^{-7}p - 4.62 \times 10^{-12}p^2, \qquad p \text{ in kg/cm}^2.$$

There follow now three semi-conductors. The specific resistance of these is so low that no error is introduced by the conductivity of the AgCl.

Silver Sulfide. The resistance of Ag_2S under pressure has already been measured [78] by Montén to 3,000 kg/cm², who found that the resistance drops at 3,000 by a factor of approximately 15, with much curvature in the pressure-resistance relation.

Material for the present measurements was prepared by heating Kahlbaum's "K" sheet silver, 0.010 inch thick, to 300° for 2 hours submerged under Kahlbaum's "K" sulfur. The metal appeared completely transformed. A piece 0.004 inch thick was filed to a width of 0.030 inch and mounted in the regular way in the AgCl sandwich. The initial resistance was of the order of megohms, so that a special arrangement of the circuits was necessary. One successful run was made. The resistance at first drops very rapidly with pressure. Up to 25,000 the relation between pressure and logarithm of resistance is linear, resistance dropping by a factor of 6,500 at 25,000 kg/cm². This would mean a drop by a factor of 2.9 for 3,000, much less than the factor 15 found by Montén. At 25,000 the curve of log(resis) against pressure becomes concave upward and continues smoothly to 58,000, where resistance has dropped by a factor of 180,000 compared with initial. At 58,000 an accelerated drop begins, continuing to 67,000, where resistance has dropped by an additional factor of 10. The presumption is that this accelerated drop means a polymorphic transition. At 67,000 the accelerated drop ceases and from here to 100,000 resistance drops by a further 35 per cent with normal upward curvature. The behavior above 67,000 is thus qualitatively like that of a metal, and the presumption is that the high pressure modification is metallic. On release of pressure the transition and the very large change of resistance at low pressure were confirmed.

Copper Sulfide (Cu_2S). Only one run was made. The specimen was ground out of a slug which I had synthesized many years ago by heating together weighed quantities of the elements. The thickness was 0.0035 inch and the width 0.065. Compared with silver sulfide the initial resistance is much lower and the effect of pressure much less. Up to about 32,000 the logarithm of resistance decreases approximately linearly with pressure, the total drop of resistance in this pressure range being by a factor of 8. At 32,000 an accelerated *rise* of resistance begins, continuing to 40,800 with total increase of resistance by a factor of 9, that is, bringing the resistance back to 12.5 per cent above the initial value. From 40,800 to 85,000 logarithm of resistance drops with minor irregularities and strong upward curvature on the average by a factor of 2.5 on the resistance. Between 85,000 and 100,000 there is an accelerated drop by an additional

factor of 2.7 on the resistance, probably due to another transition. On release, the presence of the two transitions was confirmed, but not the details of the variations.

Molybdenite (MoS_2). The material was natural crystals originally obtained by Professor G. W. Pierce many years ago from Eimer and Amend in connection with his experiments on rectifying contacts. For the present measurements it was cleaved to 0.0037 inch thickness and used in the form of a button 0.047 inch in diameter as the middle of a AgCl sandwich with three layers. The initial specific resistance was approximately 180 ohm cm. In view of the nature of the material only a single run was made. Resistance decreases with normal upward curvature from atmospheric pressure to approximately 20,000, where the resistance is 0.557 initial. Here there is an abrupt drop, doubtless due to a transition, by a factor of 2.77, to a resistance 0.201 of initial. From here to 100,000 resistance drops smoothly with normal upward curvature to a value 0.110 initial. The transition was confirmed on release of pressure. There are no previous measurements on this material for comparison.

Summary and Conclusion

The measurements just presented include 52 elements, of which 47 may be regarded as metallic. The five non-metallic elements are: carbon, silicon, germanium, selenium, and tellurium. Of the 47 metallic elements, 31 exhibit "normal" behavior of resistance under pressure, that is, a resistance decreasing with pressure with upward curvature. Included in these 31 normal metals are four with phase changes; mercury, with one freezing and one polymorphic transition; gallium, with one freezing and one transition, thallium, with one transition, and zirconium, with one transition. The discontinuity of resistance at the phase changes of these four metals also behaves "normally," that is, resistance follows the volume, decreasing with it, at the phase change. The high pressure phases of these four elements also show normal curvature (presumptive for the high pressure form of zirconium). For two of the 31 "normal" metals the decrease of resistance with pressure is not smooth over the entire range, chromium and nickel both having obtuse cusps at low pressures. The magnitude of the change of resistance of the 31 normal metals under a pressure of 100,000 kg/cm^2 varies over a wide range, being approximately 50 per cent for tin and lead and 5 per cent for cobalt and neodymium. The over-all changes of resistance of thallium and mercury are larger than 50 per cent, but these are not comparable because of the phase change. In particular, at the freezing of mercury resistance drops by a factor of 4. In general the change of resistance is less for the high melting hard metals. Certain

sets of metals are very similar: tungsten and molybdenum are indistinguishable; tantalum and columbium are very close to each other, as are also the four noble metals rhodium, palladium, iridium, and platinum.

The 16 "abnormal" metals show a wide variety of behavior. In the first place, at the phase changes of these metals resistance does not universally follow the volume, but there are three examples where resistance increases with a decreasing volume: caesium (at 22,000 kg/cm^2), barium, and bismuth (II–III).

The simplest "abnormality" is a resistance increasing with pressure. Formerly I had made the generalization that all resistance curves, whether rising or falling with pressure, could be regarded as pieces of the same curve, namely a curve concave upward. All known rising curves, with the exception of a particular orientation in single crystal antimony, were of this type, as were also all known falling curves. If this type of behavior were indeed general, then it was to be expected that presently the falling curves would pass through a minimum, and that eventually resistance would rise with pressure for all metals. This expectation was strengthened by the known minima for potassium, rubidium, caesium and barium. These new measurements over a three fold more extensive pressure range negative this generalization and add but another to my failures to prophesy new pressure effects when extending the range. Calcium is now the only metal with a smoothly increasing resistance with upward curvature over the entire pressure range. Barium would be included here except for the polymorphic transition. The resistance of high pressure barium also increases with upward curvature, but the rate of increase is very much less than that of the low pressure form and the curvature is very slight. It is to be remembered that the direction of change of resistance at the transition of barium is abnormal. Of the other metals with ultimately increasing resistance, the resistance of potassium increases smoothly over the entire range after the minimum with upward curvature, as does also that of sodium beyond the minimum, here found for the first time in about the expected place. Lithium and rubidium, however, do not rise with smooth upward curvature, but both have an intermediate episode of reversed curvature with two points of inflection. Below the electronic transition of caesium the curvature of both modifications is upward. It was unexpected to find a cusp at the electronic transition instead of a discontinuity, since the measurements of volume had given a sharp and large volume discontinuity. Instead, the effect of the electronic transition on resistance is smeared through a pressure range of 50,000 kg/cm^2. It is to be considered whether the inflections and reversals of curvature of lithium and rubidium are to be explained by some sort of electronic rearrangement, analogous to but less drastic than that of

caesium. The maximum of strontium involves a reversal of curvature followed by a second reversal with ultimate rise of resistance with upward curvature. Comment has already been made on the fact that the pattern of resistance change is quite different from that of volume change under pressure, the latter showing two discontinuities at pressures straddling the maximum of resistance. In explanation the possibility of abnormally large effects from the shearing components of stress is to be considered.

The four rare earth metals, lanthanum, cerium, praseodymium and neodymium are all abnormal and the abnormality of each is of a different type. Initially the resistance of lanthanum drops with downward curvature (one of very few examples), then passes through a much smeared out transition, and eventually passes through a minimum and ultimately rises with upward curvature. Cerium presumably passes through an "electronic" transition with large drop of resistance beyond which there is a minimum with rise terminated by a cusp beyond which resistance drops. The resistance of praseodymium at first passes through a very flat minimum, followed by a cusp and a second minimum. The former volume measurements had shown no volume discontinuity corresponding to the cusp. The resistance of neodymium varies over the entire range less than any of the other metals studied here except cobalt, and passes through a very flat minimum at about the middle of the range.

The three metals arsenic, antimony and bismuth all show abnormal behavior. Arsenic in most orientations passes through a minimum followed by a maximum, the curvature still being downward at the top pressure; this curvature must of course reverse at higher pressures. There is one orientation of arsenic in which the resistance drops over the entire range, but with reversals of curvature paralleling those of the mean orientations with minimum. The curvature of this one orientation also remains abnormally downward at the top pressure. The resistance of a presumably average orientation of antimony at first rises with the usual upward curvature, which presently reverses with a maximum and an eventual second reversal of curvature so that at the top pressure resistance is dropping with normal upward curvature. Bismuth at first increases with usual upward curvature; at the first transition there is an abnormally large drop, at the second transition an abnormal rise, followed at the third transition by a normal drop, beyond which resistance drops normally over the rest of the range with normal and slight upward curvature. No trace was found of the further two transitions in this range known from the volume measurements.

Finally, of the abnormal metals, the resistance of manganese at first drops with normal upward curvature followed by a reversal to downward curvature, followed again by a second reversal back to normal upward.

The full significance of this is not clear because of the two per cent admixture of copper, but it is to be remembered that the crystal structure of manganese is highly complex and abnormality is therefore not surprising.

Consider next the non-metallic elements. Carbon in the form of single crystal graphite drops in resistance at first with normal upward curvature, followed by reversal to abnormal downward curvature which persists to the highest pressure. The numerical magnitude of the change for graphite is that of a median metal. For the behavior of the semi-conductors silicon and germanium there seems no simple generalization; results on different specimens have not the desired reproducibility, the behavior alters entirely depending on whether the conductivity is n-type or p-type, and there are large variations of resistance with marked episodes for which the detailed description in the body of the text should be consulted. The resistance of selenium and tellurium drops so rapidly with pressure that a logarithmic scale has to be used. Further, both show abrupt drops at a median pressure indicating polymorphic transitions, that of tellurium coinciding with one already known. Beyond the transition of tellurium the behavior is like that of a normal metal. The absolute values of the changes of resistance for these two substances found under the present arrangements are much less than those previously found with pressure transmitted by a true liquid, so that it is probable that the effects of non-hydrostatic components of stress are unusually important here.

Turning now to the nine intermetallic compounds, these, contrary to expectation, showed no particular features. Two of these rise in resistance with pressure — the other seven fall. The curvature of all is normal — upward, except for a very slight reversal at the upper end of the range by AgZn. The curvatures do not vary regularly with the absolute magnitude of the effect, but there are several examples of crossing of the resistance curves. The range of numerical magnitudes is within that exhibited by the metallic elements.

The iron-nickel alloys somewhat unexpectedly showed more feature than the intermetallic compounds. These have been sufficiently summarized in the text; reversals of curvature abound.

The three semi-conductors Ag_2S, Cu_2S, and MoS_2 show no single type of behavior; the behavior of all is complicated by the entrance of new polymorphic forms. In general comment on the semi-conductors, the magnitude of the pressure effects is much larger than for the metals.

In general comment on the results, the wealth of feature at high pressures is striking. This wealth of feature does not include any special tendency for resistance to pass through a minimum with pressure, as had been anticipated from measurements below 30,000. However, a number

of examples of minima were found. With regard to wealth of feature, it is obvious that the mechanism responsible for resistance is much more sensitive in this regard than the mechanism responsible for change of volume, previous measurements of volume to 100,000 kg/cm^2 having given no intimation of the feature shown by the resistance. It would seem that the time is now ripe for another theoretical attack on the general problem of the effect of pressure on resistance. It would seem highly probable that electronic rearrangements within the lattice or the atom will be important, something already suggested by caesium and cerium. It would seem natural to associate the various reversals of curvature of other metals with analogous electronic rearrangements, less drastic than for caesium and cerium. In this connection the abnormal results for the four rare earth metals is suggestive, the electronic structure of the atoms of these metals being such as to offer particularly fertile opportunity for rearrangement.

I am especially indebted to Mr. Charles Chase, without whose unusual skill in assembling and constructing the apparatus these measurements would not have been possible.

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